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Examination of the Correlation between Shear Strength, California Bearing Ratio, and Index Properties of Fine-grained Soil

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Dedication

Dedicated to my parents for their unconditional love, inspiration, and support.

Abstract

California Bering Ratio (CBR) is used to evaluate the strength of the pavement materials by comparing bearing capacity of the material with that of a high-quality crushed stone. This test adopted by transportation agencies and widely used in the design and analysis of pavement. Several agencies developed design thickness chart based on the CBR values of the subgrade. However, CBR test is time consuming and expensive to perform compared to shear strength test and therefore several studies have been conducted to establish correlation between shear strength and CBR. The published correlation models between CBR and shear strength of soil are based on a limited number of soil test. As the required pavement thickness is directly related to the subgrade strength, misuse of correlation could lead to poor designs in practice. The aim of this study is to examine the published correlation models. Soil samples were collected from four regions in US. Various shear strength tests were conducted to investigate the factors affecting soil strength properties and the results from these tests are presented and discussed.

Table of Contents

List of Tables

List of Figures

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

The California Bearing Ratio (CBR) test was developed by the California Division of Highways and widely adopted in pavement engineering design practice. The CBR values of different soil depend on the soil parameters like gradation, mineral type, and compaction parameters, density, and shear parameters (Timani and Jain, 2019). The CBR is an important input property in the structural design of pavement. The required pavement thickness can be determined based on the CBR of the foundation soil. Even though it is one of the common design procedures for pavements, the CBR design procedure has been criticized as being empirical, overly simplistic, and outdated. Further, the CBR values are often estimated using correlation equations as the CBR test is time-consuming and difficult to operate (Huang, 2004).

In general, the soil for the CBR test is kept submerged in water for 96 hours to account for adverse moisture conditions in the field, but the unsoaked CBR test is also used to assess the strength of the soil in normal conditions. Instead of CBR, the Illinois department of transportation uses Illinois Bearing Ratio (IBR) and Immediate Bearing Value (IBV) and the Florida department of transportation uses Lime rock Bearing Ratio (LBR). All those tests are performed with slightly different procedures but with the same aim of determining the subsoil strength as well as how much the soil will expand or swell (Anderson, 2005). These tests are explained briefly in SECTION 2.2. While CBR is used in pavement thickness design, the undrained shear strength of soil is used for the design of embankment. Various laboratory and field shear strength tests are used to determine the soil shear strength. Unlike the CBR test, the shear strength tests are relatively fast and easy to determine soil properties for thickness design.

In 2004, the American Association for State Highway and Transportation Officials (AASHTO) released Mechanistic-Empirical Pavement Design Guide (MEPDG). In the MEPDG, the resilient modulus is used to characterize unbound pavement materials. The resilient modulus is a measure of stiffness for unbound materials under cyclic loading conditions. AASHTO provided a graphical correlation of the resilient modulus of unbound materials to empirical soil properties such as CBR and Hveem R-value. (See Figure 1. 1)

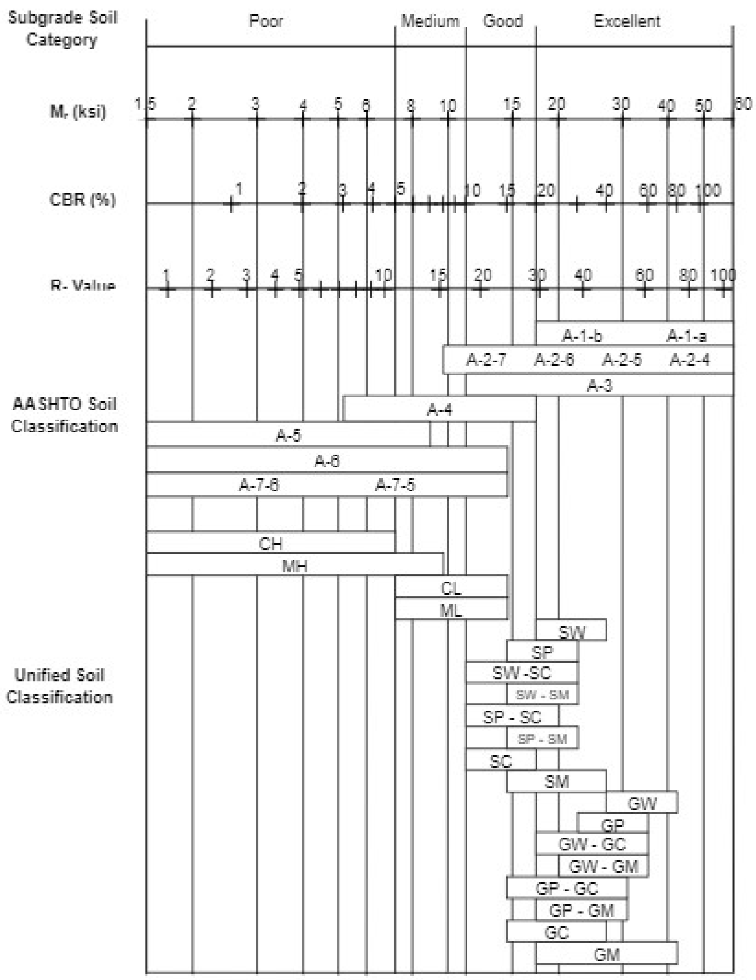


Figure 1. 1. Typical Resilient Modulus Correlations to Empirical Soil Properties and Classification Categories. (ARA, Inc., ERES Consultants Division).

Although transportation agencies implemented the Mechanistic-Empirical pavement design method, CBR based empirical design process is still used in practice for the design of low volume roads and gravel-surfaced roads. For this reason, Decky et al. (2016) suggest that the CBR is the most widely used laboratory test for testing the quality of earth structures despite its disadvantages. According to Timani and Jaine (2019), the CBR value is widely accepted as a performance indicator of a flexible pavement denoting the potential strength of subgrade materials and is dependent on many soil factors like gradation, mineral type, and compaction parameters, density, and shear parameters.

The CBR method of pavement thickness design was adopted by the United States Army Corps of Engineers and refined over the years (Gonzalez, Baker, Bianchini, 2012). The CBR thickness design procedure considers subgrade soil strength, the magnitude of the wheel load, and a number of load repetitions. Figure 1. 2 shows an example of USCOE aggregate surfaced pavement design curves.

The design subgrade shear strengths can be determined by correlation with cone index values and CBR (See Figure 1. 3). For example, in Figure 1. 3, it can be seen that CBR of 1% equals to a shear strength of 4.8 psi.

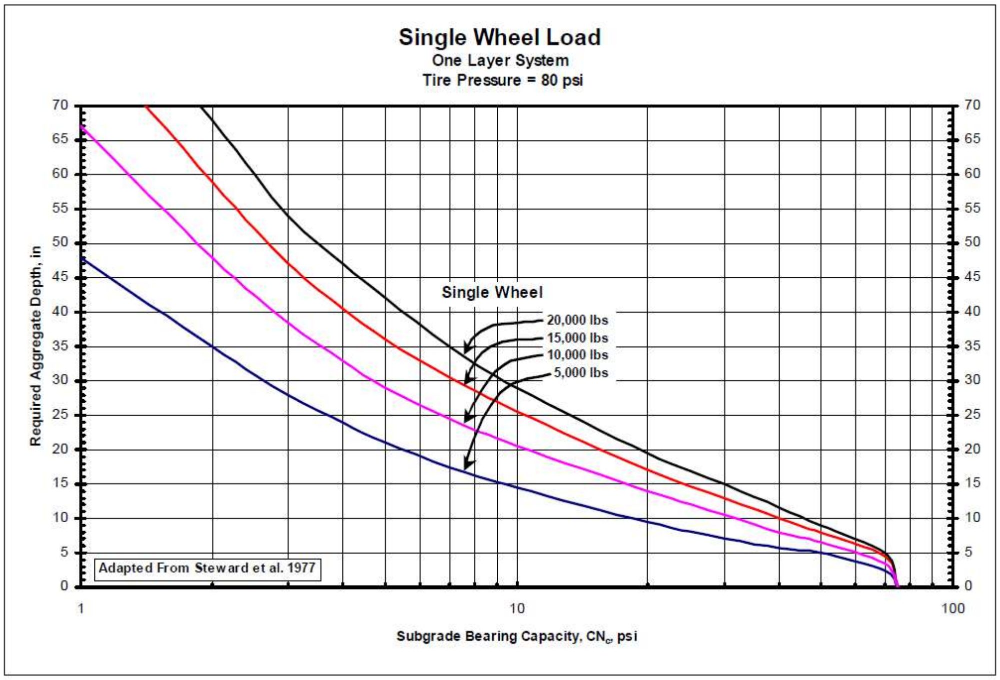


Figure 1. 2. USCOE Aggregate-surfaced pavement design curves (U.S. Army Corps of Engineers)

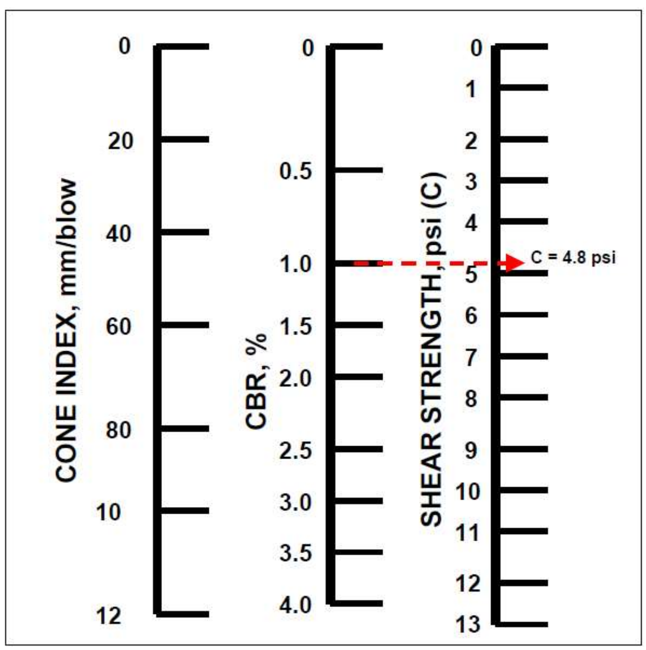


Figure 1. 3. Relationship Between Shear Strength CBR and Cone Index (U.S. Army Corps of Engineers)

One of the disadvantages of the CBR test is that the assumption of partly saturated subgrade conditions often results in a conservative design (ASTM D-18 international, 1949). This conservative estimation of the subgrade strength might lead to unnecessary expensive over design pavement. Gregory and Cross (2007) also pointed out the 96 hours of soaking following compaction is a setback of using the CBR test. Moreover, the CBR test requires a large bulk soil sample compared to other strength tests and it is difficult to get enough materials from standard size borings through the existing pavement during the street reconstruction. Black (1979) explains the disadvantage at present is that the commonly used calibrated penetrometer used in the CBR test has an undefined factor of safety implying that the equipment reads strength values that are less than the real ones. Its calibration makes no allowance for differences in the behavior of remolded and undisturbed soils.

As the CBR test is relatively expensive and time-consuming, however, several attempts were made to develop a correlation between shear strength and soil index properties with CBR values of soil. However, the difference in final design strength could be fairly dramatic depends on the correlation used. Therefore, an extensive review of the available correlation equations is needed to improve the reliability of the design.

1.2 Scope of This Study

- Perform comprehensive literature review of the previous research on the correlations between CRB and other soil properties.
- Conduct laboratory tests including Atterberg limit test, and hydrometer test on four (4) different soils from Georgia, Illinois, Mississippi, and California respectively; to classify

the soils based on the Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO).

- Conduct the unsoaked CBR tests, and shear strength tests at 4 different moisture contents for each soil to investigate the effect of moisture on CBR and shear strength. Shear strength values of soil are measured using torvane, pocket penetrometer, cone penetrometer, and Unconfined Compressive Strength test.
- Study and examine the results of the tests performed, compare them to the existing correlations, and conclude the similarities.

1.3 Significance of The Study

The CBR test is one of the commonly used tests in measuring the strength of the soil either in both geotechnical and pavement engineering. However, due to the limitation of the CBR test, conversion from other soil properties is often used to determine the design CBR value. The significance of this study is to examine the existing correlation between the CBR and shear strength of the soil by comparing the existing correlations and the results from different tests performed on different soils in the laboratory. Additionally, comparing the soaked CBR test with the unsoaked CBR test, the unsoaked test is faster and easier to perform, whereby you do not have to soak the sample for 96 hours. Therefore, the unsoaked CBR test will be used in this study and the results will be converted to the soaked CBR values to see their correlation. If they have a good correlation, then the unsoaked CBR can be adapted instead of the soaked CBR in order to save time.

This study will help engineers to measure soil strength and get CBR of the soil in a much shorter time, and in a non-complicated way, if the existing correlations agree with the results in the tests performed in this study. In addition to that, it will also help improve the designs of both geotechnical/foundation and pavement design, given that a better correlation would avoid over-design and under-design.

CHAPTER 2. Literature Review

2.1. Introduction

The performance of pavement depends upon the quality of subgrades. A subgrade should be prepared to provide firm support for the construction of pavement layers. The required pavement thickness is determined based on the subgrade strength. Accurate characterization of the strength of the in-situ subgrade soil is therefore critical for the long-term performance of the pavement section. This chapter presents tests used to measure the CBR and shear strengths of soil. Published relationships between CBR value, soil index properties, and shear strength are also discussed in this chapter.

2.2. Test Methods Used to Obtain CBR and Shear Strength of Soil

2.2.1. CBR tests

2.2.1.1. Standard CBR test procedure (AASHTO T193 and ASTM D1883)

The CBR test is the strength test that compares the penetration resistance of a material with that of a crushed stone. In general, clay has a CBR value of less than 20%, while high-quality crushed stones have a value between 80% - 100%. Typical ranges of CBR values of various types of soil can be found in Figure 1. 1.

The piston load is applied at a strain rate of 0.05 in. (1.3 mm)/min and the load required to penetrate 0.1 in. (2.5 mm) and 0.2 in (5.1 mm) of the test material CBR are recorded for calculation (AASHTO T 193). The test apparatus is shown in Figure 2. 1 . Correlation curves are used to get the CBR for the target dry density (See Figure 2. 2). Typically, compacted soil samples are soaked in water for 96 hours before applying the load to simulate long term field conditions. The swelling of the soaked soil is monitored during a four-day soaking period (See Figure 2. 3).

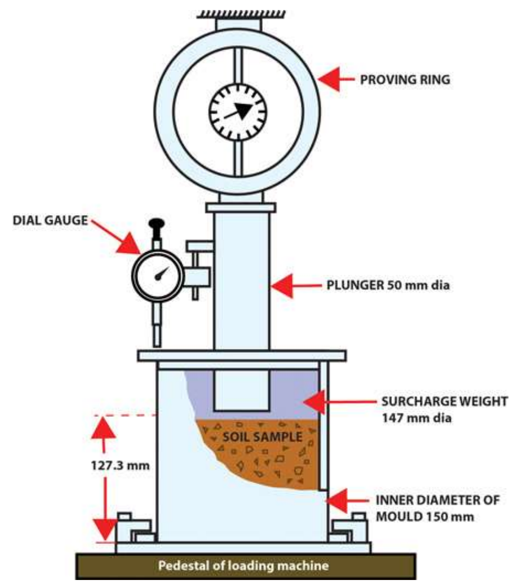


Figure 2. 1 Penetration Test (Source: Benjamin E Backus, globalgilson.com)

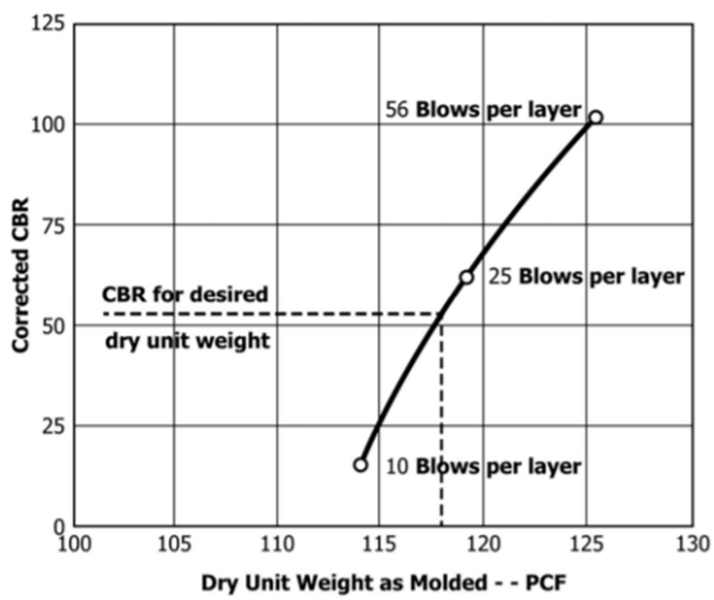


Figure 2. 2 Dry unit weight Vs CBR (ASTM D- 1883- 16)

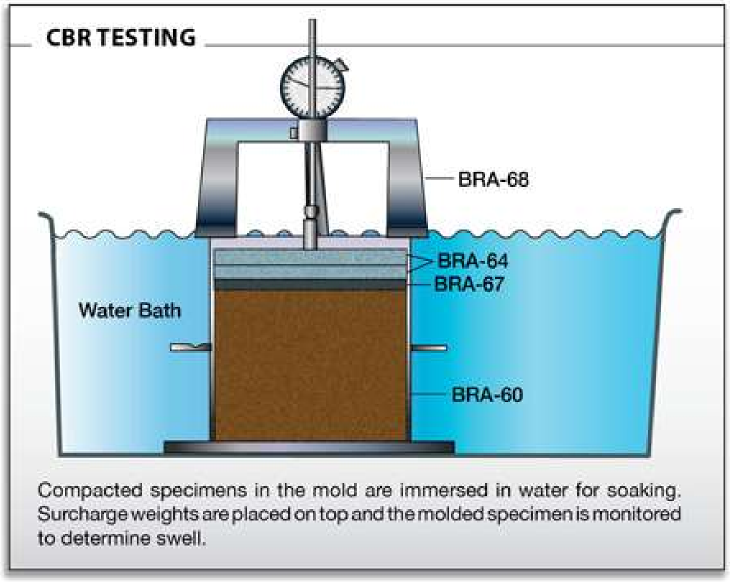


Figure 2. 3 Soaked sample (Source: Benjamin E Backus, globalgilson.com)

Unsoaked CBR test is also used for determining the CBR of treated or untreated subgrade materials prepared at a range of moisture contents. For untreated soil, the test is conducted immediately after compacting the material, according to AASHTO T 99, without soaking it in water. For chemically modified soils, the test is conducted 24 hours after compaction to allow for curing, without soaking in water. The unsoaked CBR is primarily be used for determining the subgrade stability under construction traffic, the need for subgrade treatment, and the depth of treatment.

Arshad et al, 2018 investigated relationship between the soaked and un-soaked CBR. Both unsoaked and soaked CBR tests were performed with silty clay soil samples obtained from six different site. The result is presented in Figure 2. 4.

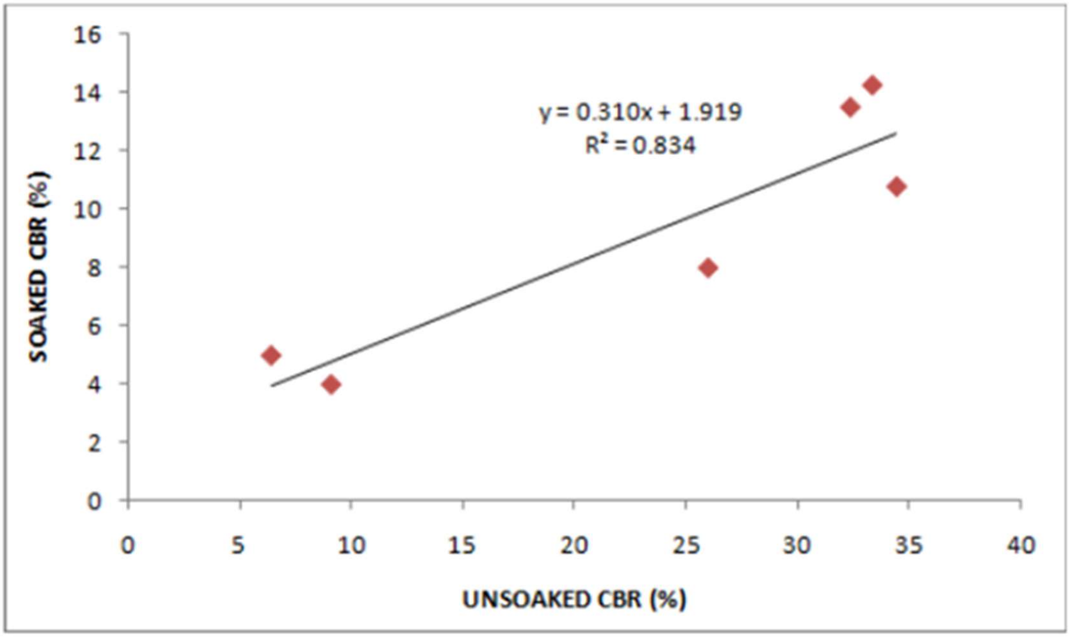
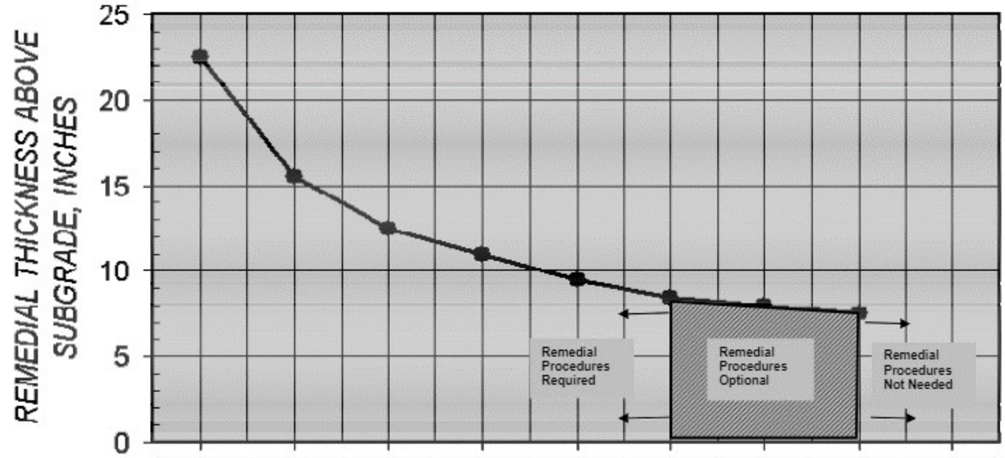


Figure 2. 4 un-soaked vs soaked CBR (Arshad et al, 2018)

2.2.1.2. Illinois Department of Transportation Procedures

The Illinois Department of Transportation (IDOT) slightly modified the standard CBR test procedure. The Illinois Bearing Ratio (IBR) and the Immediate Bearing Value (IBV) are practically the same as soaked and unsoaked CBR. Unlike the standard CBR test, the IBR value is calculated at 5 mm (0.2 in.) penetration. The IBV testing is conducted immediately after compacting the material without soaking the soil sample in water. Different size mold is used depends on the soil type. Soils with > 10% clay (and < 90% silt and/or sand) are compacted in 100 mm (4 in.) mold and the soils with < 10% clay (and > 90% silt and/or sand) is compacted in 150 mm (6 in.) diameter mold. The subgrade with an IBV value less than 6.0 is considered an unstable foundation and requires to be treated before pavement construction.

Based on the subgrade IBV value, the required fill thickness can be determined from the chart in Figure 2. 5.



IBV	1	2	3	4	5	6	7	8	9
Cone Index(CI)	40	80	120	160	200	240	280	320	360
Shear Strength (psi)	2.25	4.50	6.75	9.00	11.25	13.50	15.75	18.00	20.25
Qu (tsf)	0.32	0.64	1.00	1.28	1.60	1.94	2.24	2.56	2.88
Rate (in./Blow)	4.6	2.6	2.0	1.5	1.3	1.1	1.0	0.9	0.8
Rate (Blows/6")	1.3	2.3	3.0	4.0	4.6	5.5	6.0	6.7	7.5
Treatment Thickness	22.5	15.5	12.5	11	9.5	8.5	8	7.5	0

Figure 2. 5 IDOT Subgrade treatment thickness chart

2.2.1.3. Florida Department of Transportation Procedure

Florida Department of Transportation (FDOT) uses Lime rock Bearing Ratio (LBR) instead of CBR. The test procedure is the same as CBR except for the penetration resistance to crushed lime rock in Florida is used as the standard reference. In general, LBR yield a slightly higher value than CBR.

2.2.1.4. Dynamic Cone Penetration (DCP)

The Dynamic Cone Penetrometer (DCP) was developed by the Army Corps of Engineers is used to measure the in-situ strength of the soil. The DCP penetration rate (penetration depth/blow) is used to determine the in-situ CBR of the soil. The dynamic cone penetrometer uses an 8 kg (17.6 lb) hammer. Figure 2. 6 shows the DCP apparatus. The standard hammer is recommended for stiffer soil (CBR greater than 10%) while the 4.6 kg (10.1 lb) hammer is used for clay soil with CBR of less than 10%.

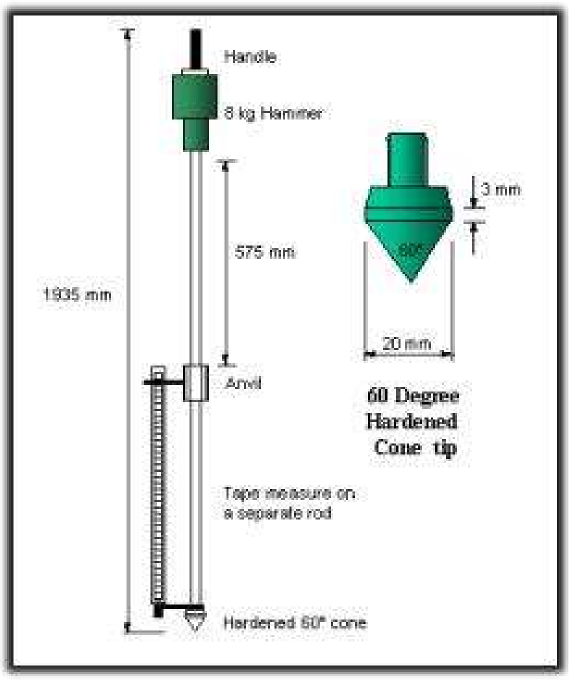


Figure 2. 6 Dynamic Cone Penetrometer (Source: ASTM D6951M-18)

The following equation recommended by the U.S. Army Corps of Engineers can be used to determine field CBR values of soil:

With 8kg hammer: $CBR = \frac{292}{Penetration\ Rae\ (\frac{mm}{blow})}$ (Eqn 2. 1)

With 4.6 kg hammer: $CBR = \frac{1}{0.017019 \times Penetration\ Rae\ (mm/blow)^2}$ (Eqn 2. 2)

2.2.2. Shear strength tests

2.2.2.1. Unconfined Compressive Strength Test

The undrained shear strength of clays is commonly determined from an unconfined compression test. The undrained shear strength of clay is equal to one-half the unconfined compressive strength. The unconfined compression test is usually performed on a cylindrical sample with a diameter to-length ratio of 1:2 (ASTM D2166M-16). Unconfined soil tester is shown in Figure 2. 7.

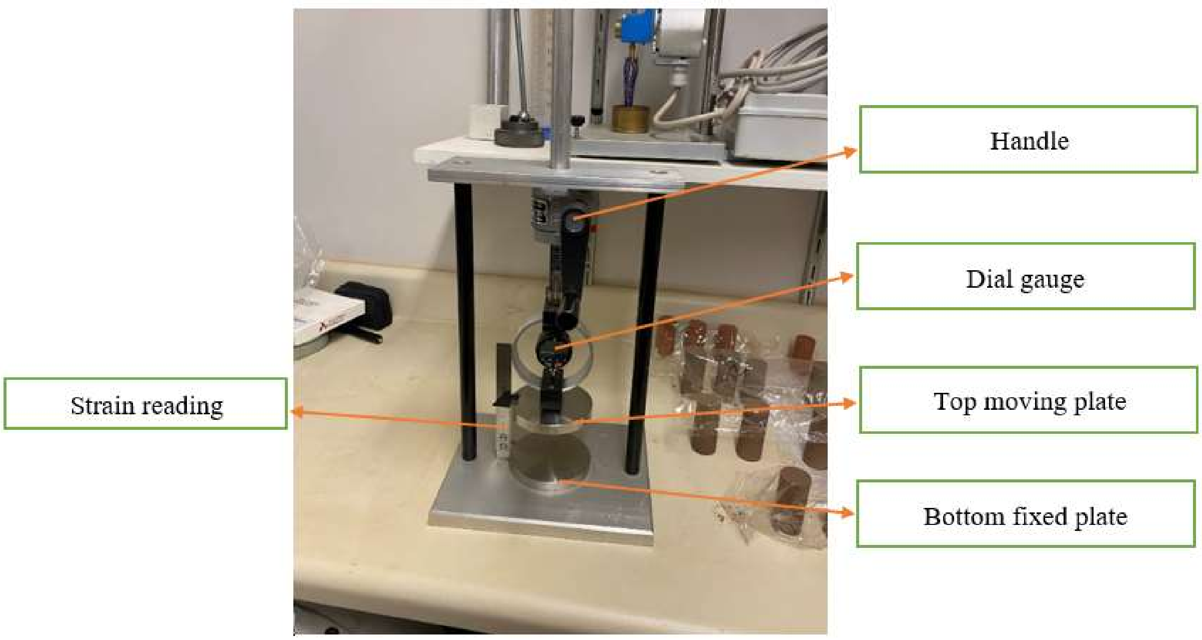


Figure 2. 7 Unconfined Compressive strength loading machine

2.2.2.2. Vane shear test

The vane shear test is designed to measure the undrained shear strength of cohesive soils. It is easy to perform, and the equipment is not expensive compared to those of the CBR test apparatus. The test does not apply to sandy soils or non-plastic silts that allow drainage during the test. The vane is a four-bladed material, usually constructed from steel or steel treatment processes such as hardening. See Figure 2. 8.

The torque required to shear a cylindrical surface of the soil is used to calculate the shear strength of soil using the following equation:

For a rectangular vane of H/D = 2;

$$Su = \frac{6T}{7\pi D^3} \qquad \text{(Eqn 2. 3)}$$

The values are stated in either SI units or inch pound units

Where:

Su = peak undrained shear strength from the vane, kPa [lbf/ft^2],

T = maximum value of measured torque (T_{max}) or residual torque (T_R) corrected for apparatus and rod friction, N·m [lbf·ft],

D = vane diameter, mm [in.]

The shear strength can be correlated to the CBR (ASTM D 2573-72).

Figure 2. 8 Vane shear tester with different blades

2.2.2.3. Static Cone Penetrometer (SCP)

The SCP was developed by the US Army Corps of Engineers for use to quickly check the traffic ability of soil in the field. The SCP (see Figure 2. 9) is lighter and less difficult to use than the DCP. The SCP is conducted by pushing the cone slowly into the soil by hand for field application, and it may be machine-mounted for laboratory use. The measured Cone Index (CI) can be converted to the unsoaked CBR and unconfined compressive strength of the soil.

The relationship of CI and the un-soaked CBR is given by:

$$CBR = \frac{CI}{40} \qquad \text{(Eqn 2. 4)}$$

Where, CI = Cone Index (psi)

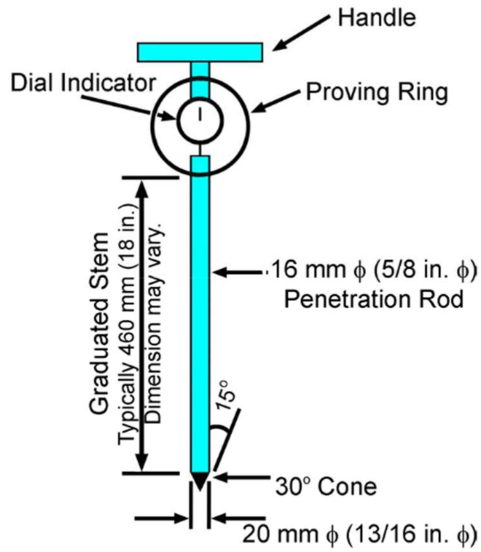


Figure 2. 9 Static Cone Penetrometer. (Source: Illinois Department of Transportation Bureau of Bridges and Structures)

2.3. Correlation of CBR and Shear Strength

Measuring CBR using in-situ methods can be quick and convenient. Black (1979) states that the standard dynamic cone (DCP) is one of the most commonly used tests to measure the CBR of the subgrade of the soil because it has the advantage of performing large numbers of measurements without destruction and disturbing the soil, especially when testing an existing pavement. The DCP can be carried out through a conventional core hole without excessive damage to the pavement. Based on s series of comparative evaluation with clay soils, Black (1979) suggested the following relationship between the CBR and undrained shear strength (Cu), with the equation:

$$CBR = \frac{C_U}{23} \qquad \text{(Eqn 2. 5)}$$

Black (1979) observed that the undisturbed over-consolidated soils failed at a much smaller strain compared to the remolded soils. The average strain to failure of undisturbed soils being only a quarter of that of remolded soils. The work of Skempton and analysis of in-situ CBR tests carried out at the laboratory indicates that in undisturbed over-consolidated soils, the stress beneath the CBR plunger at a standard penetration of 2.5 mm is normally greater than 75 % of the stress when ultimate bearing capacity has been attained. Hence, it can be assumed that the CBR test measures the stress at the ultimate bearing capacity of undisturbed over-consolidated soils. That would transform the Eqn 2.5 above to be:

$$CBR = \frac{C_u}{11.5} \qquad \text{(Eqn 2. 6)}$$

Gregory and Cross (2007) investigated the correlation between shear strength of soil and CBR value by modeling piston in the CBR test as a circular foundation. The bearing capacity of the foundation on cohesive soil is directly related to its shear strength. The following correlation formulas were developed between the CBR and the ultimate bearing capacity of cohesive soils.

$$CBR = \frac{q_{ult} \times 100}{6895} = \frac{6.2 \times \mathrm{Cu} \times 100}{6895} = 0.09\ Cu \text{ (SI Units)} \qquad \text{(Eqn 2. 7)}$$

$$CBR = \frac{q_{ult} \times 100}{1000} = \frac{6.2 \times \mathrm{Cu} \times 100}{1000} = 0.62\ Cu \text{ (English Units)} \qquad \text{(Eqn 2. 8)}$$

The correlation of CBR with shear strength parameters was verified by comparing correlated CBR with actual AASHTO T193 CBR results of 5 different soils. Although a limited number of soil samples were used in verification, the correlated CBR and laboratory-measured CBR values are in good agreement (see Figure 2. 10).

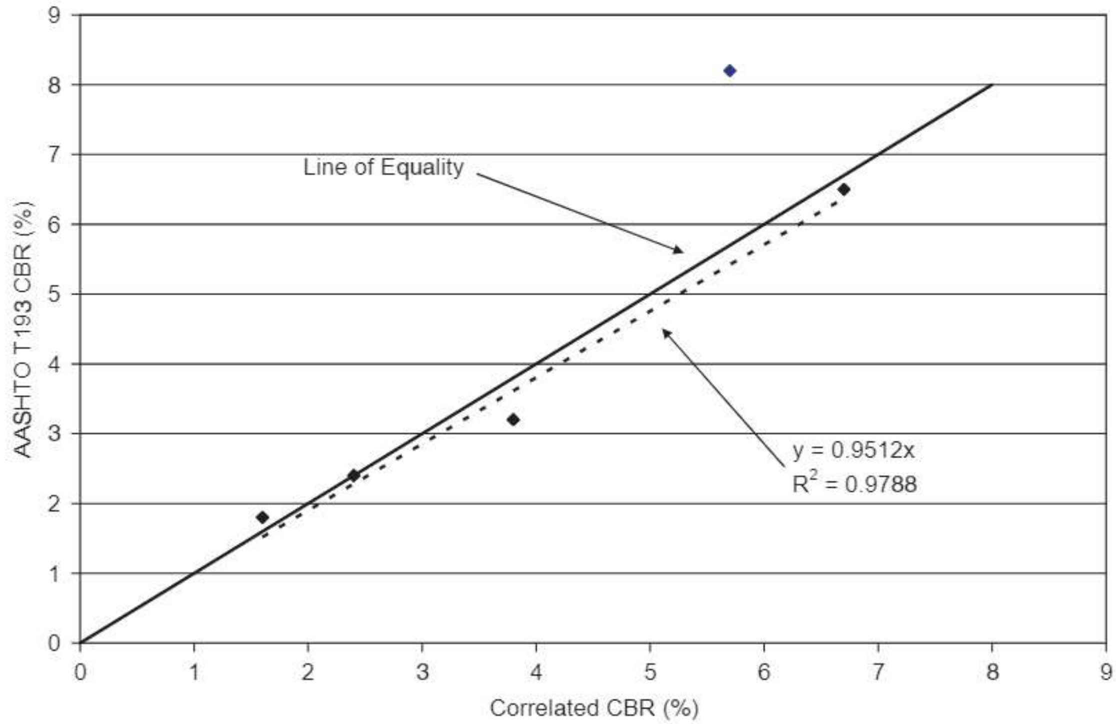


Figure 2. 10 Comparison between correlated CBR and laboratory CBR values (Gregory and Cross, 2007)

Purwana and Nikraz (2014) investigated the correlation between unsaturated CBR and the unsaturated shear strength of the sand-kaolin clay mixture using the suction-monitored direct shear. Suction is defined as the ability of the soil to absorb additional water, and the relationship between water content and soil suction is that the higher the soil water content, the lower section in the soil. The tensiometer was attached to the conventional direct shear to monitor suction. The tensiometer is placed in such a way that its ceramic surface has good contact with the specimen as seen in Figure 2. 11. The results are shown in Figure 2. 12 indicated that the correlation between the CBR and the unsaturated shear strength depends on the normal stress applied on the soil.

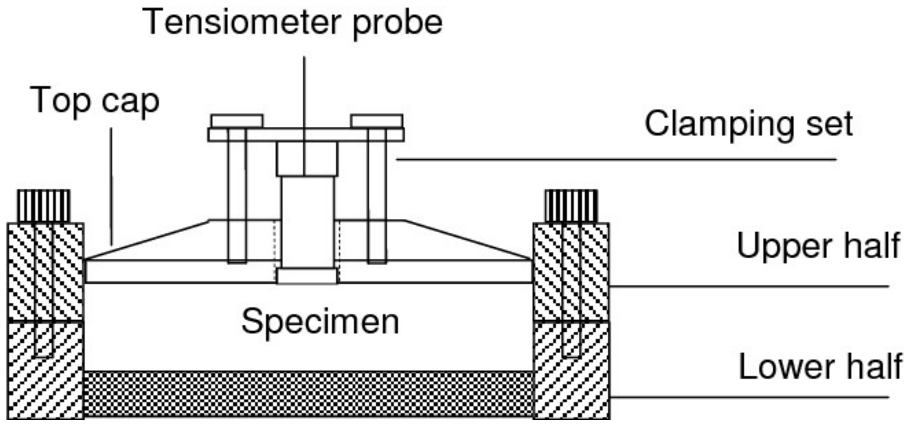


Figure 2. 11 Cross-section of suction-monitored direct shear apparatus (Purwana et al., 2011)

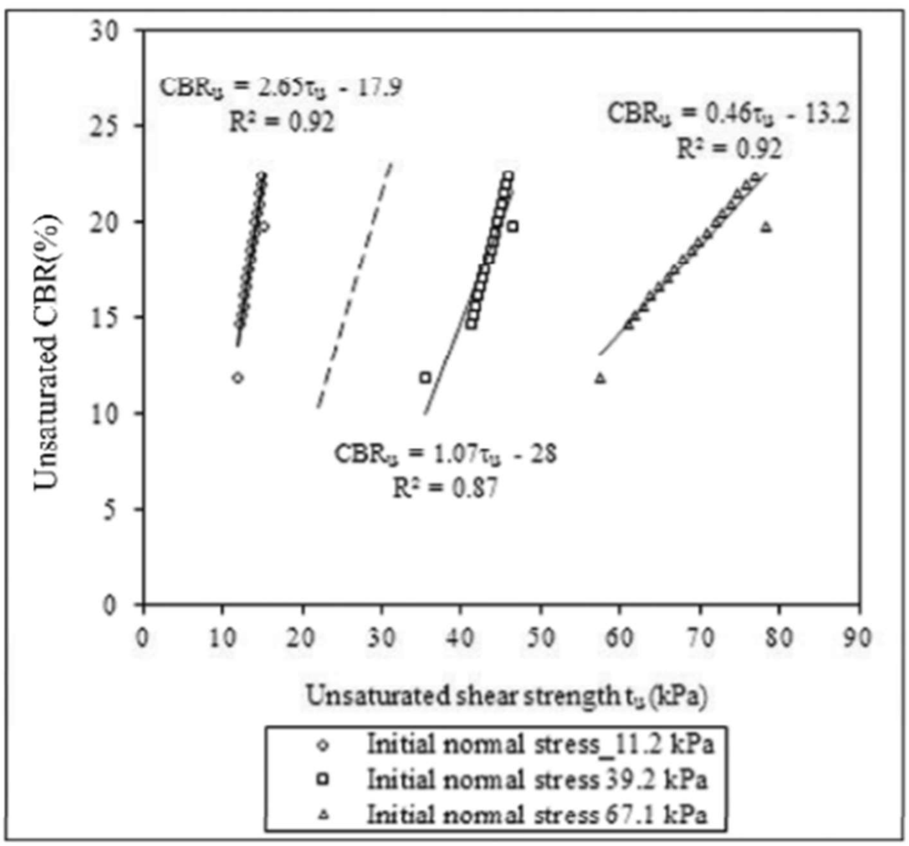


Figure 2. 12 Unsaturated shear strength Vs CBR for sand (Purwana et al., 2011)

Danistan and Vivulanan-dan (2009, 2010) investigated the relationship between CBR values (un-soaked) and undrained shear strength using artificial CH soils. Soil samples were prepared by mixing bentonite, kaolinite, and sand to create artificial CH soils. The PI of the soil samples ranges from 35.38% to 70.99%. Figure 2. 13 shows the variation of undrained shear strength and CBR values of CH soil. Additional tests were conducted with CL and SC soils.

The following correlation formulas were developed for different types of soil:

For CH soil: $Cu\ (kPa) = -\ 0.426\ (CBR)^2 + 2.212\ (CBR)$ (Eqn 2. 9)

For CL, CH, SC soils: $CBR = 0.56\ Cu\ (kPa)^{1.07}$ (Eqn 2. 10)

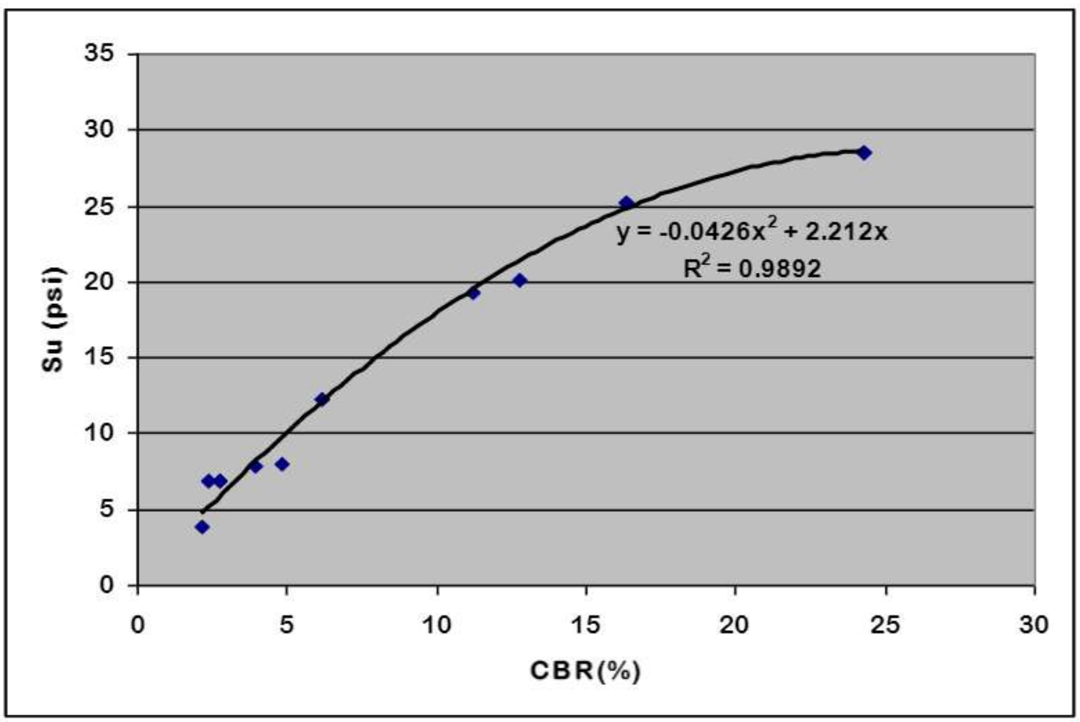


Figure 2. 13 Variation of shear strength with CBR values (Danistan and Vivulanan-dan, 2009,2010)

For a low CBR range (for CBR less than 5), Giroud and Han (2004) introduced the following correlation equation between the shear strength and the CBR for the design of geosynthetic reinforced gravel-surfaced road:

$$C_u\ (\text{kPa}) = 30 \text{ x CBR} \quad \text{(Eqn 2. 11)}$$

The USCOE relationship between CBR and shear strength presented in **Error! Reference source not found.** is plotted in Figure 2. 14 USCOE relationship between shear strength and CBR below and equation 2.12 is drawn from the graph. Lastly, based on the information presented in the IDOT Subgrade treatment thickness chart (Figure 2. 5), equation 2.13 is determined.

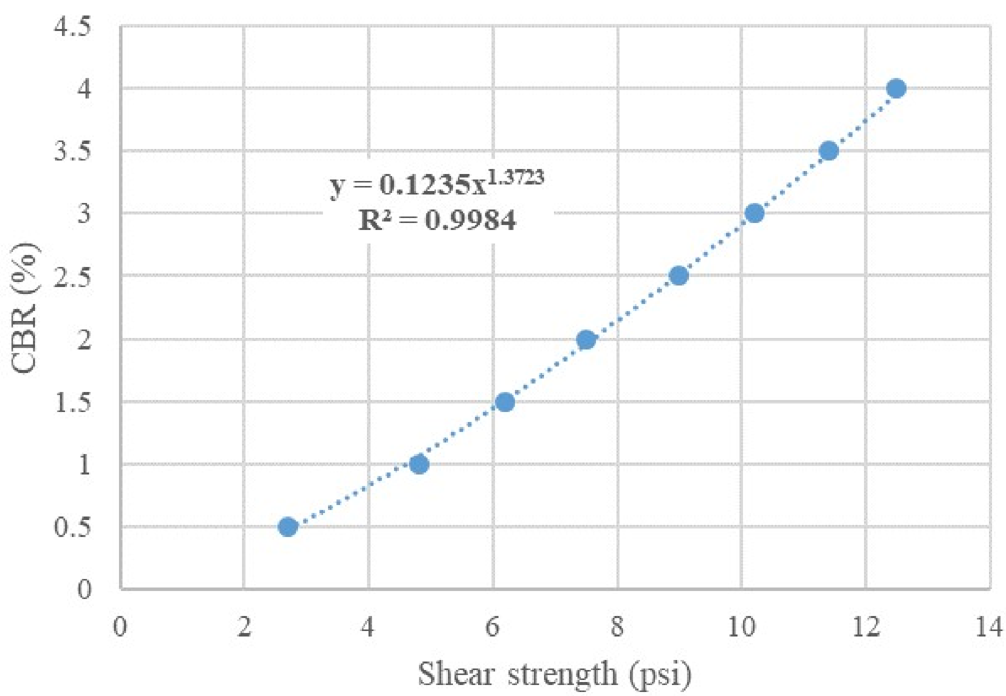


Figure 2. 14 USCOE relationship between shear strength and CBR

$$CBR = 0.1235C_u^{1.3723} \qquad \text{(Eqn 2. 12)}$$

where, Cu (psi)

$$CBR = 0.444\ C_u\ (psi) \qquad \text{(Eqn 2. 13)}$$

Error! Reference source not found. is prepared to summarize the CBR and shear strength relationships discussed in this section. For better comparison, the formulas were written as CBR= A* Cu, whereby “A” is a constant.

Table 2. 1 Summary of CBR and Shear Strength Correlations

Reference	Equation	Equation #
Black (1979)	$CBR = 0.043\ C_u$ (kPa) $CBR = 0.30\ C_u$ (psi)	2.5
Black (1979)	$CBR = 0.087\ C_u$ (kPa) $CBR = 0.60\ C_u$ (psi)	2.6
Gregory and Cross (2007)	CBR = 0.09 Cu (kPa) CBR = 0.62 Cu (psi)	2.7 and 2.8
Giroud and Han (2004)	CBR = 0.033 Cu (kPa) CBR = 0.23 Cu (psi)	2.11
USCOE	$CBR = 0.0087\ C_u\ (kPa)^{1.3723}$ $CBR = 0.1235\ Cu\ (psi)^{1.3723}$	2.12
IDOT	$CBR = 0.064\ C_u$ (kPa) $CBR = 0.444\ C_u$ (psi)	2.13

The differences in the predicted CBR values between correlation equations are illustrated in Figure 2. 15.

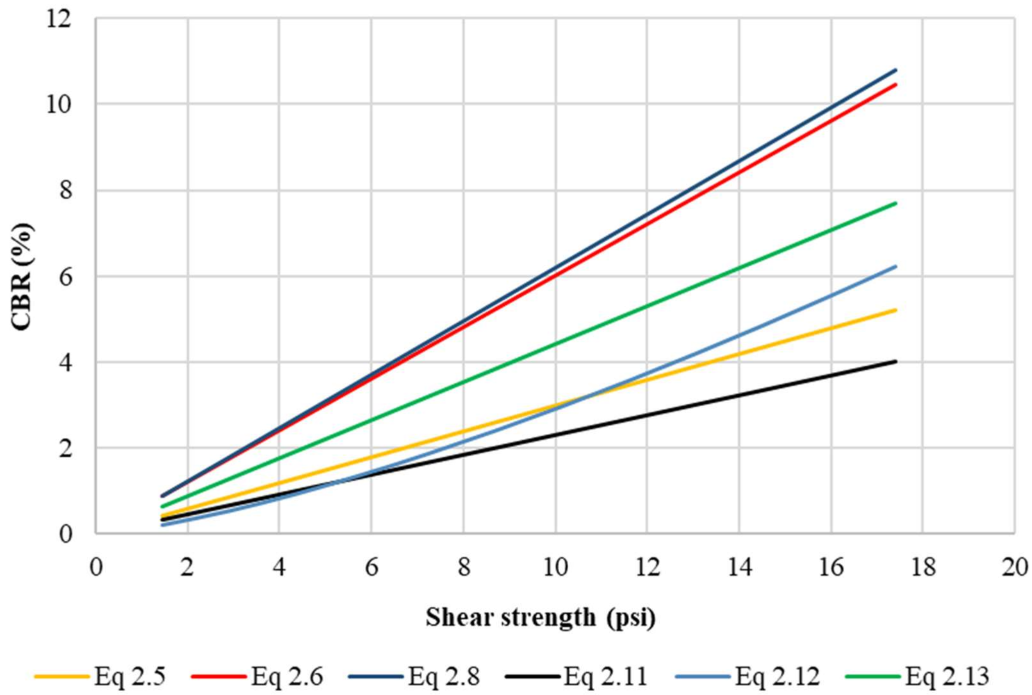


Figure 2. 15 Relationships between CBR and shear strength

The Giroud-Han (2004) equation predicts the lowest CBR value while the equations developed by Black (1979), Gregory, and Cross (2007) predict the highest CBR value for the same shear strength. Both Black (1979), Gregory and Cross (2007) assumed the CBR as a bearing capacity of a circular foundation. It is important to note that the bearing capacity factors used in their equation assume that general shear failure occurs in the soil. For soft soil, local shear failure may have occurred, and the bearing capacity factors should be reduced.

2.4. Correlation of CBR and Soil Index Properties

Faisal et al. (2017) studied relationship between CBR, Atterberg limits, and Optimum Moisture Content for high plastic silts, clay, and shale soil types. In their study, seven samples were used to obtain the liquid limit (LL), plastic limit (PL), plastic index (PI), particle size distribution, OMC, MDD, and CBR values (from both soaked and unsoaked CBR) to study their relationships, and came up with the following correlations:

$$CBR_{soaked} = 11.2525\,(LL) - 26.4144(PI) - 0.3024(\%F) + 153.7175 \quad \text{(Eqn 2.14)}$$

$$CBR_{unsoaked} = 17.3174(LL) - 42.5467(PI) - 102.9336(MDD) + 455.515 \quad \text{(Eqn 2.15)}$$

Where MDD is in mg/cm^3.

In addition, Olumide and Olamiyi (2018) also conducted a study on the relationship between CBR and soil index properties to get a correlation between CBR and the MDD of poorly graded sand with gravel using an empirical, analytical model. Eighteen samples were used in this study, and the following correlation between CBR and MDD was introduced:

$$CBR = MDD\,[0.252\,(MDD) - 1] + 0.993 \quad \text{(Eqn 2.16)}$$

Where CBR is in KN, and MDD in mg/m^3

Timani and Jain (2019) investigated the effect of moisture content on CBR values of clay-sand-gravel. In this study, nine different mixtures of clay (5 % clay increment from 10% to 50%) soil samples were prepared at five moisture conditions; one at Optimum Moisture Content (OMC), two moisture conditions on wet side of OMC at 2 percent and 3.5 percent, and two moisture conditions on dry side of OMC at 2 percent and 3.5 percent. For all mixtures, **Error! Reference source not found.** it was evident that CBR decreases as water in the sample reached to wet side of OMC. Experiments conducted with dry side of OMC showed larger value of CBR. Therefore, it is advised to compact subgrades in road pavement construction on dry side of OMC to achieve maximum strength.

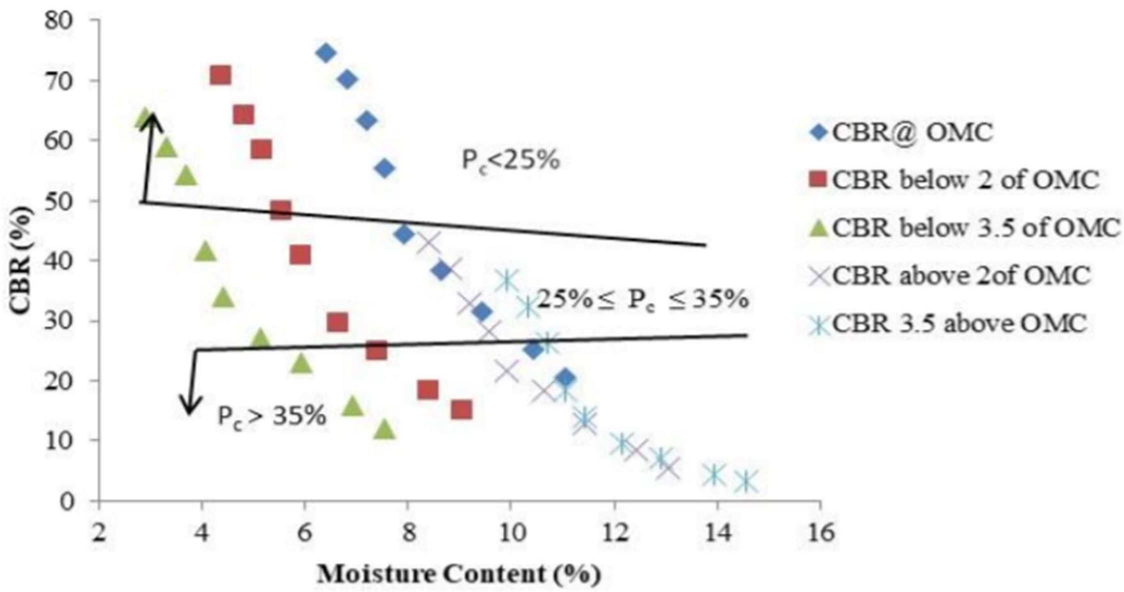


Figure 2. 16 Moisture content vs CBR (Timani, 2019)

CHAPTER 3: MATERIALS AND TEST PROCEDURES AND METHOD

3.1 Soil Properties and Classification

The soil samples were collected from four different locations in the US, California, Illinois, Mississippi, and Georgia. Engineering index tests were conducted per ASTM standards at Kennesaw State University Geotechnical Engineering laboratory. The engineering index test conducted in this study includes; Atterberg limits (ASTM D 4318), moisture content (ASTM D 2216), hydrometer analysis (ASTM D 7928), (ASTM D 854), USCS classification (ASTM D 2487), and AASHTO classification (AASHTO T88). Figure 3. 1 shows soil samples used in this study.

Figure 3. 1 Soil samples (From left, MS soil, IL soil, GA soil and CA soil)

The materials engineering index properties are presented in Table 3. 1. The Atterberg limits of the soils plot above the “A” line, which puts it into the Clay region, which can be seen in Figure 3. 2. All soil samples are classified as A-7 soil as per the AASHTO classification system, indicating that the soil samples are not suitable for pavement foundation.

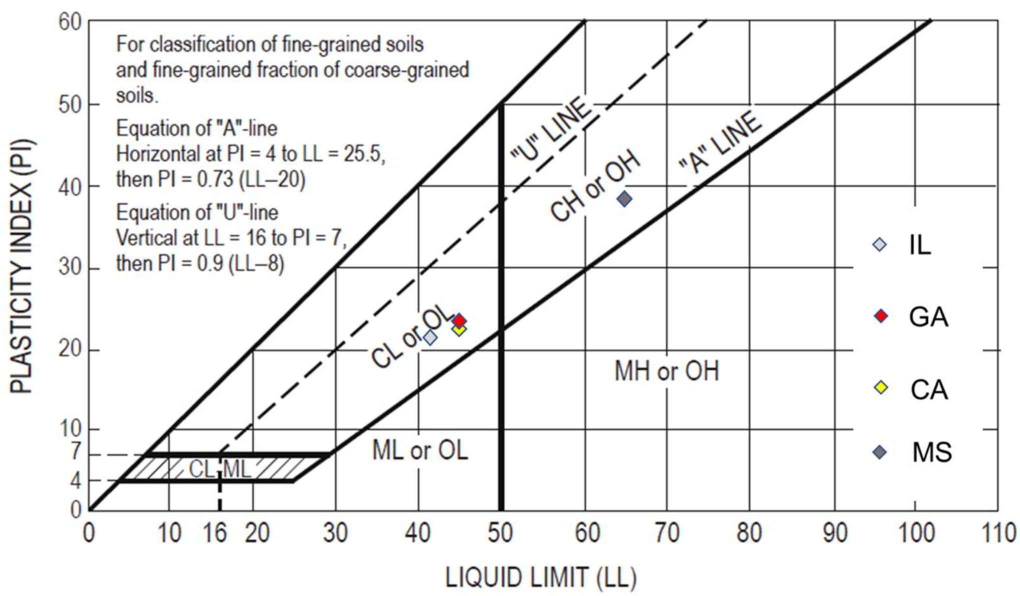


Figure 3. 2 Atterberg limits of soil samples

Table 3. 1. Engineering Index Properties of the Soil Samples

Soil ID	Source	Atterberg limits			Classification	
		LL	PL	PI	USCS Classification	AASHTO Classification
IL	Illinois	41	21	20	CL	A-7-5
GA	Georgia	46	23	23	CL	A-7-6
CA	California	46	24	22	CL	A-7-6
MS	Mississippi	65	27	38	CH	A-7-6

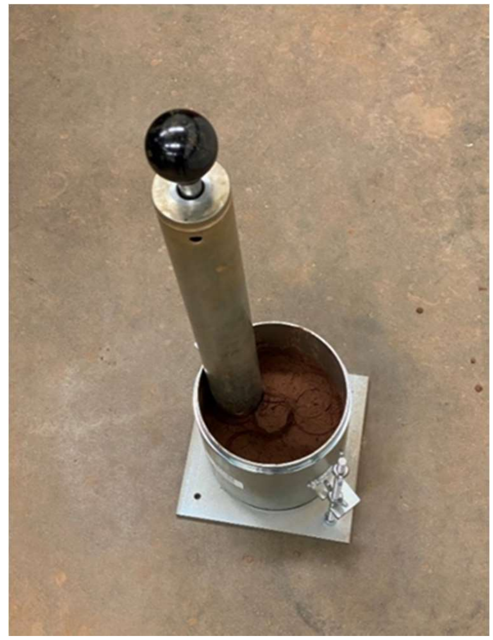
3.2 California Bearing Ratio Test

The soil samples were oven-dried at 105°C for 24 hours and the dried soils were ground in the soil grinder. For each soil sample, four specimens were prepared and tested at various moisture contents. The CBR specimen preparation was conducted in general accordance with AASHTO T193 (Standard Method of Test for the California Bearing Ratio). The sample was then compacted into a 6-in diameter mold with a height of 7-in. using standard proctor effort in general accordance with AASHTO T 99 (Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop) Method D. A metal spacer disk with a height of 2.416 in. was placed inside of the mold. Each soil sample was compacted in three lifts with 25 blows from a 5.5-lb rammer. Following compaction, the weight of each sample was recorded for the calculation of dry densities. A representative sample of the material was taken to determine the moisture content of soil samples. The CBR test specimen preparation procedure is shown in Figure 3. 3. The moisture-density relationships of soil samples are plotted in Figure 3. 4.

In this study, only unsoaked CBR values of soil samples were determined. Therefore, the test was conducted immediately after compacting the material without soaking it in water. A surcharge of annular and slotted weights was placed on the specimen before the application of load. The penetration depth and the applied load were recorded by the computer program. The CBR values of soil were obtained using the following equation. The standard unit pressure for well-graded crushed stone is 1,000 psi (6.9MPa) at 2.54 mm (0.10 in.) and 1,500 psi (10.3MPa) at 5.08 mm (0.20 in.) penetration.

$$CBR\ (\%) = \frac{Pressure\ on\ the\ piston\ for\ 0.1\text{–}in.\ or\ 0.2\text{-}in,\ penetration}{Standard\ unit\ pressure\ for\ well\ graded\ crushed\ ston} \times 100 \qquad \text{(Eqn 3. 1)}$$

(a) CBR mold with spacer disk



(b) Compaction of soil

(c) Compacted soil sample

(d) Set up for penetration test

Figure 3. 3 CBR Test Specimen Preparation

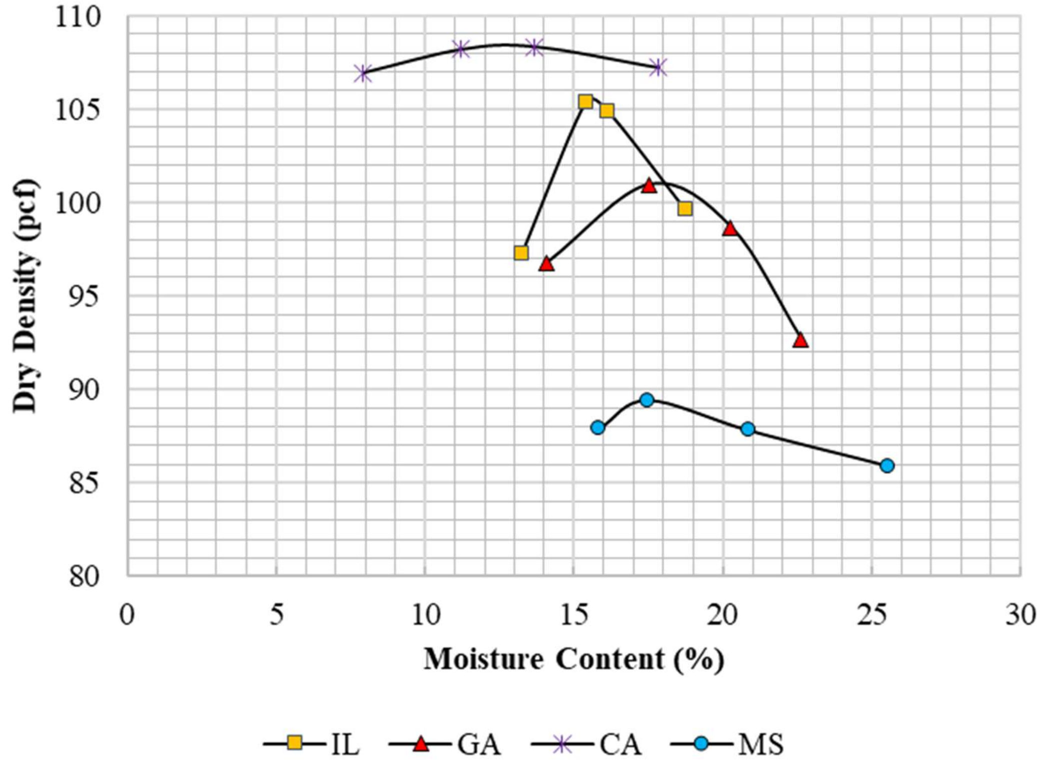


Figure 3. 4 Moisture and dry density relationships of soil samples

3.3 Shear Strength Tests

Upon completion of the CBR test, various shear tests were performed on each CBR test specimen. The shear strength of soil was measured using the pocket torvane and the pocket penetrometer on three different locations on the surface of the sample. The static cone penetration test was also performed at the center of the sample (see Figure 3. 5). The pocket torvane (also known as pocket shear vane) is designed for taking on-site measurements of the shear strength of cohesive soil. The pocket penetrometer can measure the compressive strength of the soil. It is a small handheld gauge that contains a telescoping rod that can be pushed into the soil, and the distance the rod goes into the soil corresponds to a compressive strength on the dial (Roseke, 2013).

Figure 3. 5 Shear strength measurement using Static Cone Penetrometer and Pocket penetrometer

Additional samples were prepared for Unconfined Compressive Strength (UCS) of the soil sample. The same moisture content and density were used in the preparation of specimens for UCS testing. The sample was then compacted with the Harvard miniature compaction apparatus (see Figure 3. 6). The UCS was determined for each sample according to ASTM D2166 (Standard Test Method for Unconfined Compressive Strength of Cohesive Soil).

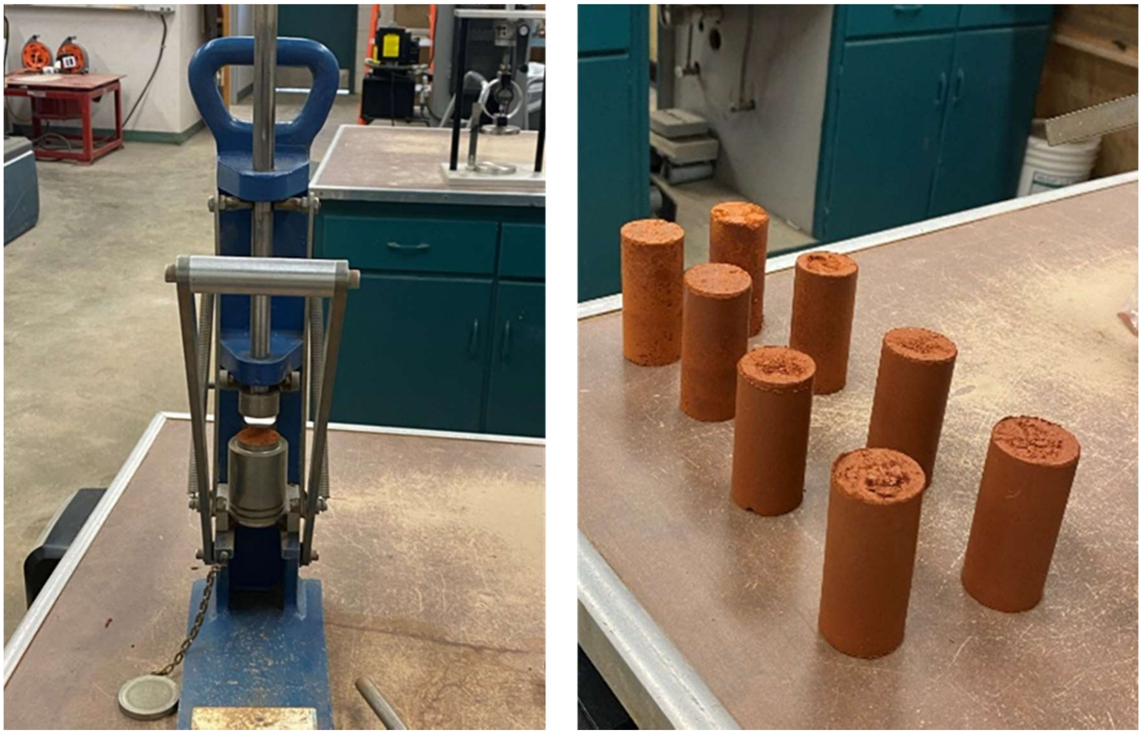


Figure 3. 6 Unconfined Compressive Strength Sample preparation

CHAPTER 4. RESULTS AND DISCUSION

4.1 Introduction

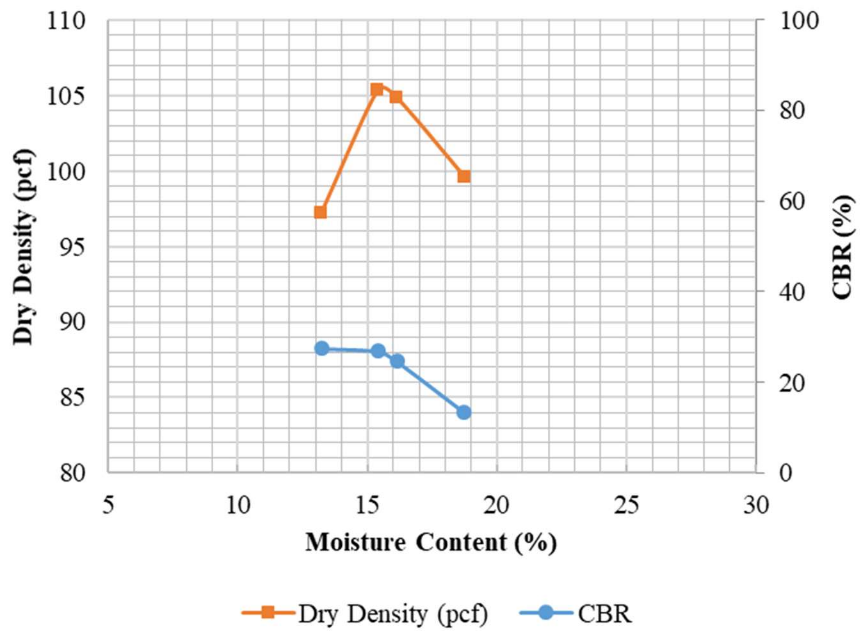
This chapter presents the results of testing conducted for this research. The CBR values are compared with shear strength values to evaluate the previous research work on the relationship between CBR and shear strength of the soil. Analysis of the test results is discussed in this chapter.

4.2 CBR, density, and moisture content relationships

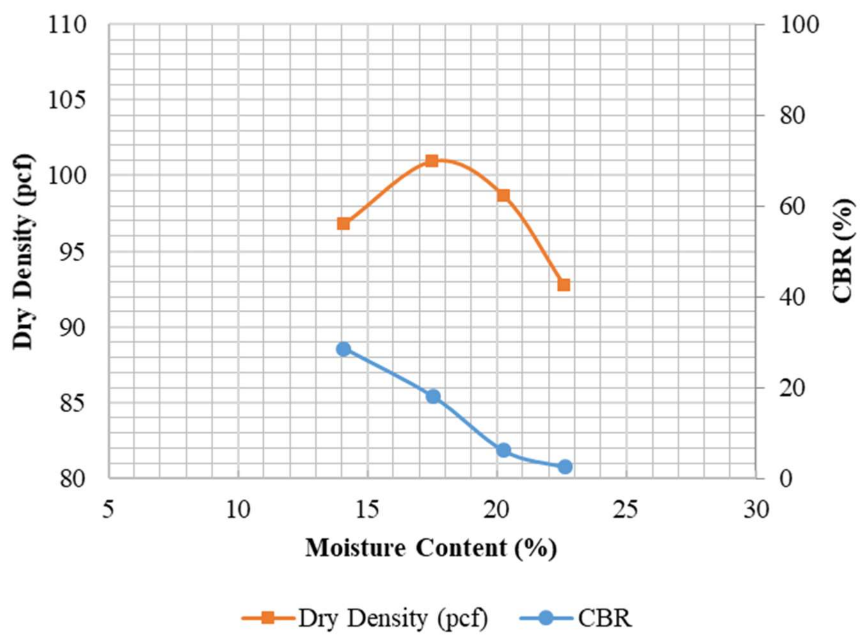
The relationship between unsoaked CBR, dry density, and moisture contents are presented graphically in Figure 4. 1. The result shows that the CBR values decrease with an increase of moisture content while the dry density increased with moisture content to a maximum dry density and decreases as moisture content increased more than the optimum. Table 4. 1 below summarizes the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the soil samples. The CBR values at MDD were determined from Figure 4. 1 and presented in Table 4. 1.

Table 4. 1 Summary of MDD, OMC, and CBR of soil samples

Soil sample	OMC (%)	MDD (lb/ft^3)	CBR (%) at OMC
IL	15.6	105.5	28.0
GA	18.0	101.0	16.0
CA	12.9	108.5	20.0
MS	17.5	89.0	22.0

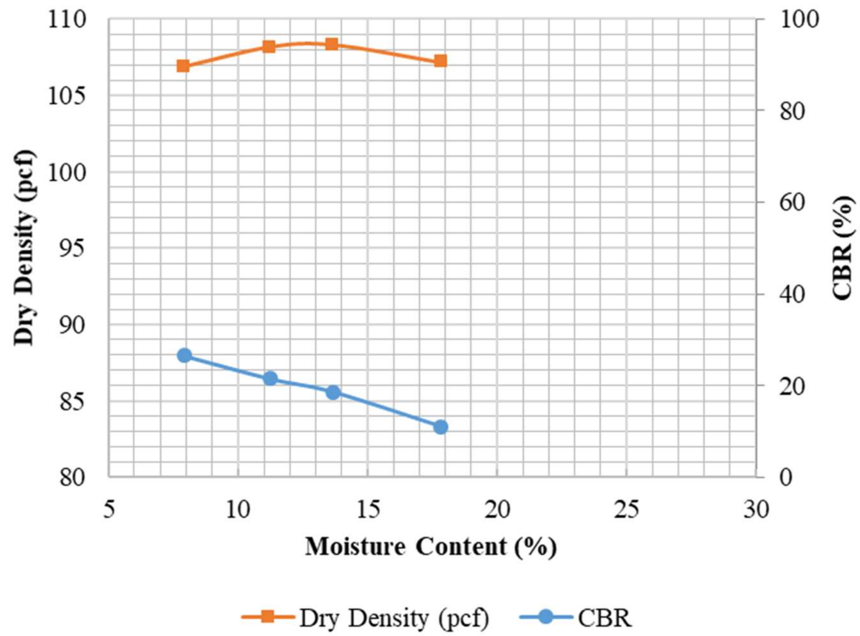


a) Soil ID: IL

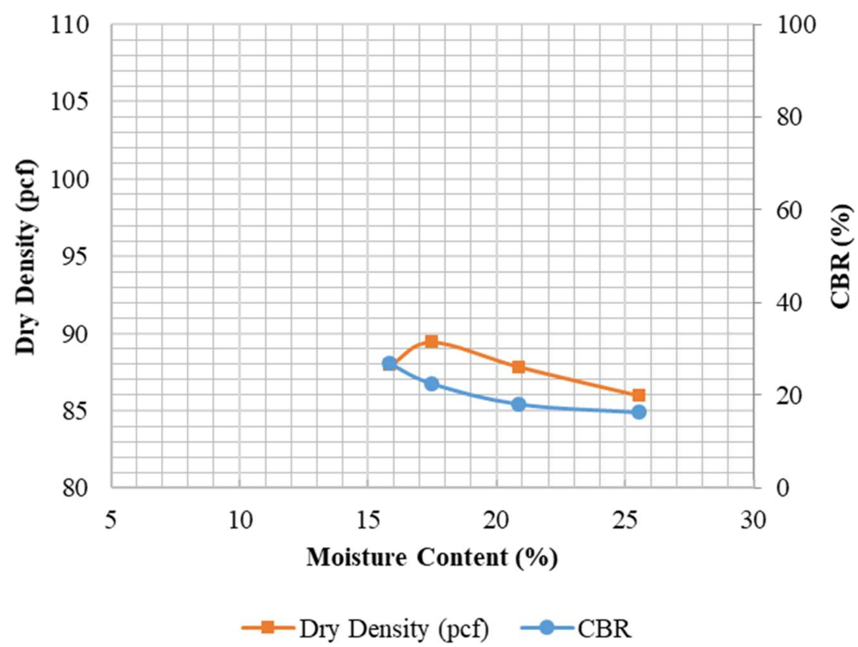


b) Soil ID: GA

Figure 4. 1 Relationship between CBR, moisture content, and dry density of soil



c) Soil ID: CA



d) Soil ID: MS

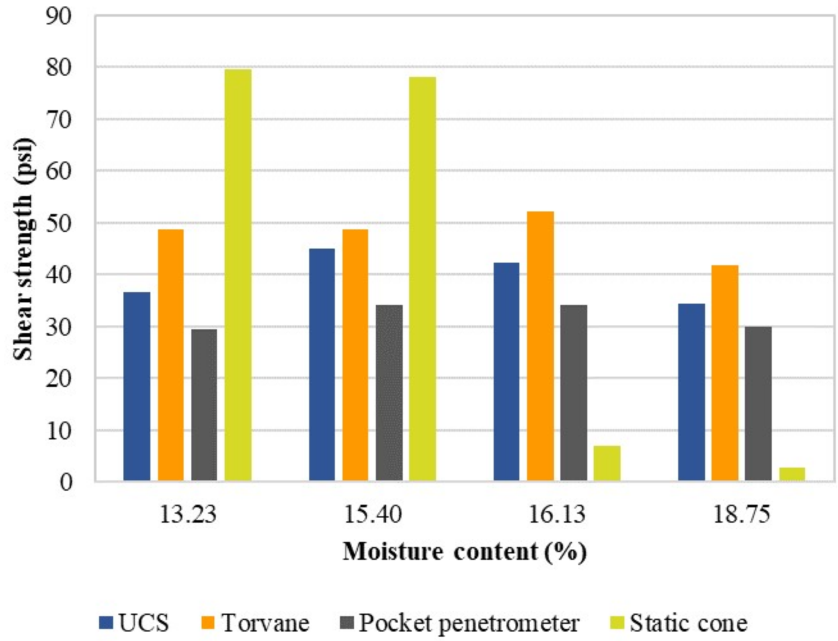
Figure 4. 1 Relationship between CBR, moisture content, and dry density of soil (Continued)

4.3 Shear strength test results

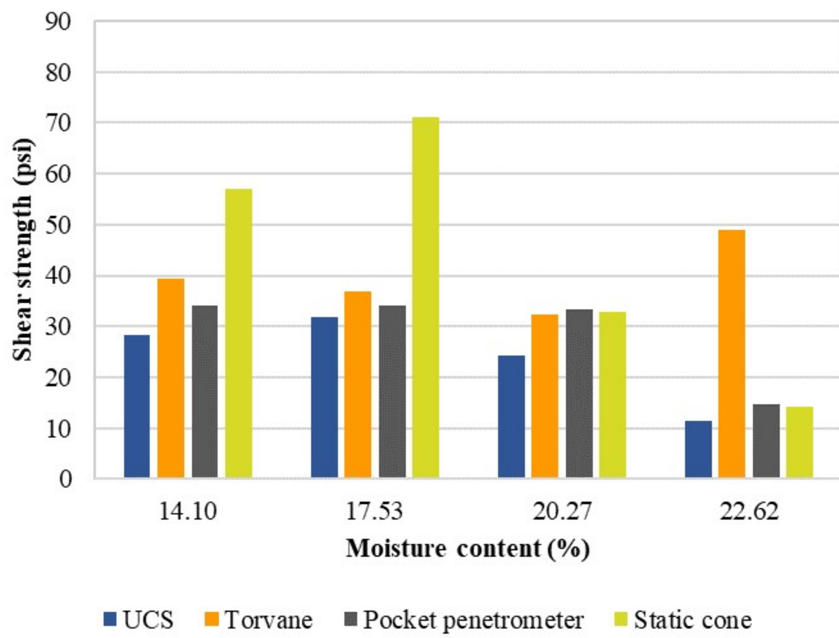
The shear strength of soil was measured using hand-held tools including the pocket torvane, the pocket penetrometer, and the static cone. Also, undrained shear strength values of soil samples were estimated from the unconfined compressive strength of the soil samples. The pocket torvane and the pocket penetrometer were used on three different locations on the surface of the sample except for the static cone tests. In UCS testing, two replicate specimens were prepared and tested for each moisture content. The average shear strength values of soil samples are presented in Figure 4. 2. The shear strength values are highly variable depends on the method used.

The mean, standard deviation, and coefficient of variation are summarized in Table 4. 2 and Table 4. 3 for the shear strength values measured with torvane and pocket penetrometer, respectively. As shown in Table 4. 2, the torvane shear strength values are highly variable, especially at high moisture contents. This result indicated that the torvane shear strength data is unreliable and cannot be used in this study. The variation of the pocket penetrometer values is very low, but changing the moisture content didn't change the shear strength values. This also indicated that the shear strength data obtained using a pocket penetrometer is unreliable.

Among all the shear strength tests, the UCS test provides the most consistent and reliable shear strength data in this study. The shear strength values, which are presented in Table 4. 4, were utilized to evaluate the relationship between shear strength and CBR.

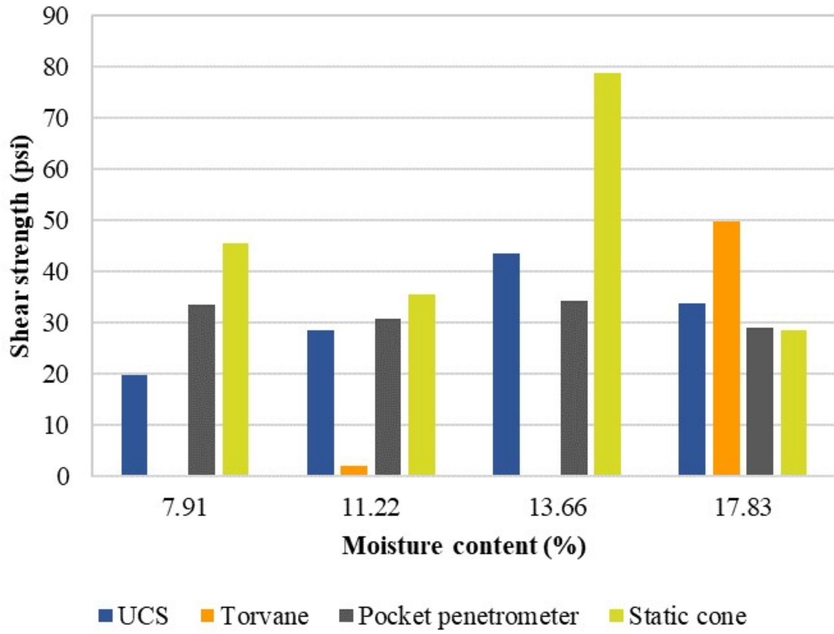


a) Soil ID: IL

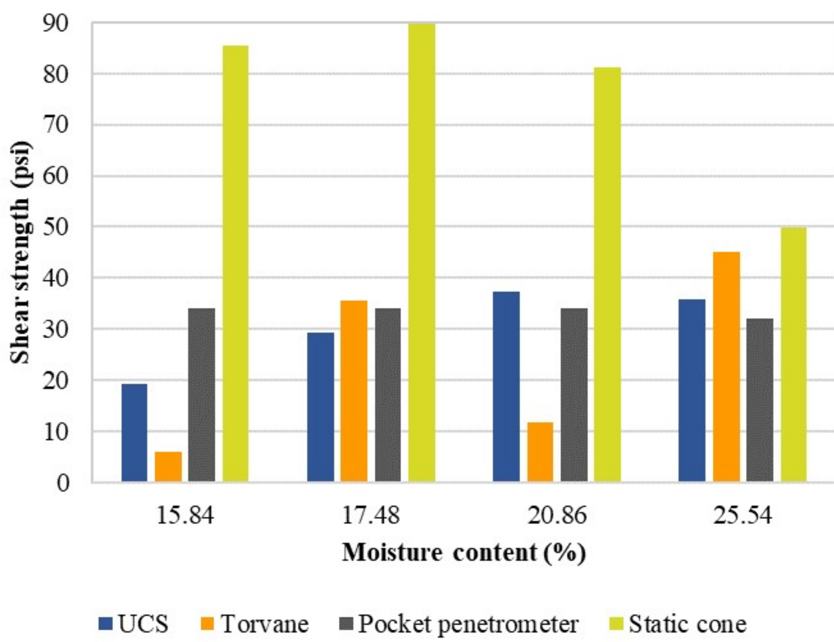


b) Soil ID: GA

Figure 4. 2 Shear strength of soil measured with UCS and hand-held tools



c) Soil ID: CA



d) Soil ID: MS

Figure 4. 2 Shear strength of soil measured with UCS and hand-held tools (continued)

Table 4. 2 Torvane shear strengths

Soil sample: IL												
Moisture content w (%)	13.2%			15.4%			16.1%			18.8%		
Trial	1	2	3	1	2	3	1	2	3	1	2	3
Shear strength (psi)	41.2	55.5	49.8	39.8	55.5	51.2	45.5	56.9	54.0	61.2	21.3	42.7
Average (psi)	48.8			48.8			52.2			41.7		
SD	7.2			8.1			5.9			19.9		
COV (%)	15%			17%			11%			48%		
Soil sample: GA												
Moisture content w (%)	14.1%			17.5%			20.3%			22.6%		
Trial	1	2	3	1	2	3	1	2	3	1	2	3
Shear strength (psi)	42.7	37.0	38.4	42.7	32.7	35.6	35.6	28.4	32.7	32.7	52.6	61.2
Average (psi)	39.4			37.0			32.2			48.8		
SD	3.0			5.1			3.6			14.6		
COV (%)	8%			14%			11%			30%		
Soil sample: CA												
Moisture content w (%)	7.9%			11.2%			13.7%			17.8%		
Trial	1	2	3	1	2	3	1	2	3	1	2	3
Shear strength (psi)	0.0	0.0	0.0	2.8	0.0	2.8	N/A	0.0	0.0	64.0	71.1	14.2
Average (psi)	0.0			1.9			0.0			49.8		
SD	0.0			1.6			0.0			31.0		
COV (%)	N/A			87%			N/A			62%		
Soil sample: MS												
Moisture content w (%)	15.8%			17.5%			20.9%			25.5%		
Trial	1	2	3	1	2	3	1	2	3	1	2	3
Shear strength (psi)	7.1	4.3	7.1	49.8	38.4	18.5	14.2	7.1	14.2	28.4	64.0	42.7
Average (psi)	6.2			35.6			11.9			45.0		
SD	1.6			15.8			4.1			17.9		
COV (%)	27%			45%			35%			40%		

Table 4. 3 Pocket penetrometer shear strengths

Soil sample: IL												
Moisture content w (%)	13.2%			15.4%			16.1%			18.8%		
Trial	1	2	3	1	2	3	1	2	3	1	2	3
Shear strength (psi)	32.7	27.0	28.4	34.1	34.1	34.1	34.1	34.1	34.1	29.9	29.9	29.9
Average	29.4			34.1			34.1			29.9		
SD	3.0			0.0			0.0			0.0		
COV (%)	10%			0%			0%			0%		
Soil sample: GA												
Moisture content w (%)	14.1%			17.5%			20.3%			22.6%		
Trial	1	2	3	1	2	3	1	2	3	1	2	3
Shear strength (psi)	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1	32.0	12.8	16.0	14.9
Average	34.1			34.1			33.4			14.6		
SD	0.0			0.0			1.2			1.6		
COV (%)	0%			0%			4%			11%		
Soil sample: CA												
Moisture content w (%)	7.9%			11.2%			13.7%			17.8%		
Trial	1	2	3	1	2	3	1	2	3	1	2	3
Shear strength (psi)	34.1	32.0	34.1	28.4	32.0	32.0	34.1	34.1	34.1	22.8	32.0	32.0
Average	33.4			30.8			34.1			28.9		
SD	1.2			2.1			0.0			5.3		
COV (%)	4%			7%			0%			18%		
Soil sample: MS												
Moisture content w (%)	15.8%			17.5%			20.9%			25.5%		
Trial	1	2	3	1	2	3	1	2	3	1	2	3
Shear strength (psi)	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1	32.0	32.0	32.0
Average	34.1			34.1			34.1			32.0		
SD	0.0			0.0			0.0			0.0		
COV (%)	0%			0%			0%			0%		

Table 4. 4 Unconfined compressive strength measurements

Soil sample: IL								
Moisture content w (%)	13.2%		15.4%		16.1%		18.8%	
Trial	1	2	1	2	1	2	1	2
UCS (psi)	74.1	72.6	92.6	87.4	83.7	85.2	65.2	72.6
Shear strength (psi)	37.0	36.3	46.3	43.7	41.9	42.6	32.6	36.3
Soil sample: GA								
Moisture content w (%)	14.1%		17.5%		20.3%		22.6%	
Trial	1	2	1	2	1	2	1	2
UCS (psi)	54.1	59.3	57.0	70.4	48.1	48.9	20.7	24.4
Shear strength (psi)	27.0	29.6	28.5	35.2	24.1	24.4	10.4	12.2
Soil sample: IL								
Moisture content w (%)	7.9%		11.2%		13.7%		17.8%	
Trial	1	2	1	2	1	2	1	2
UCS (psi)	41.5	37.0	54.8	59.3	97.8	75.6	65.2	69.6
Shear strength (psi)	20.7	18.5	27.4	29.6	48.9	37.8	32.6	34.8
Soil sample: IL								
Moisture content w (%)	15.8%		17.5%		20.9%		25.5%	
Trial	1	2	1	2	1	2	1	2
UCS (psi)	40.0	37.8	53.3	64.4	74.1	75.6	73.3	69.6
Shear strength (psi)	20.0	18.9	26.7	32.2	37.0	37.8	36.7	34.8

4.4 Relationship between CBR and Shear Strength of soil

To determine the relationship between the CBR and the shear strength, the CBR and the shear strength measured at the same moisture contents are plotted in Figure 4. 3. The data is scattered and cannot provide a reliable fit. This is because the CBR values decrease with an increase of moisture content while the shear strength increased with moisture content to a maximum and decreases as moisture content increased more than the optimum. In Figure 4. 4, the shear strength at wet of optimum conditions and corresponding CBR values are plotted.

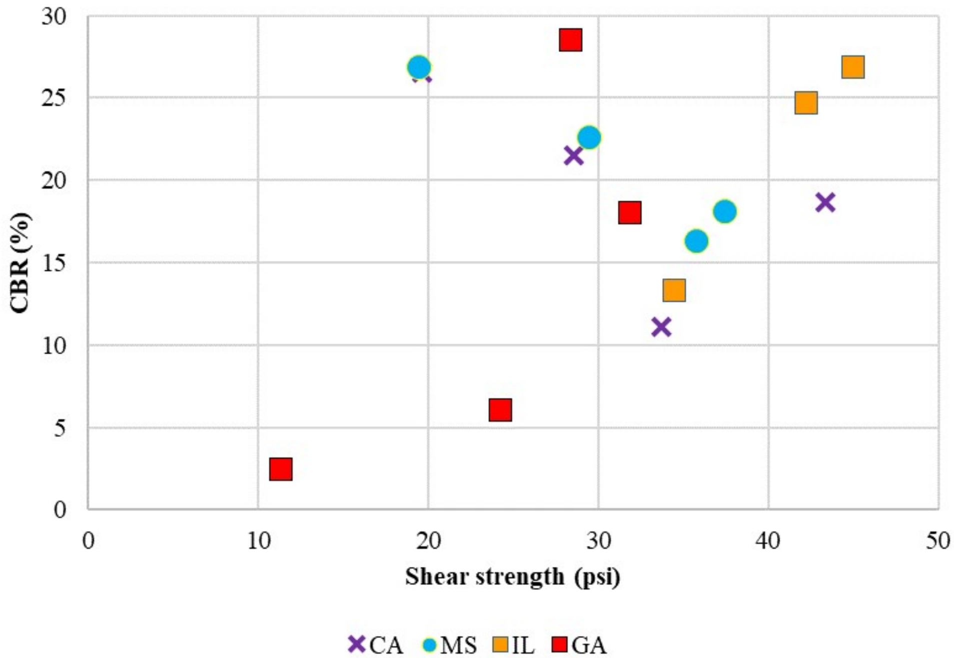


Figure 4. 3 CBR and shear strength (UCS)

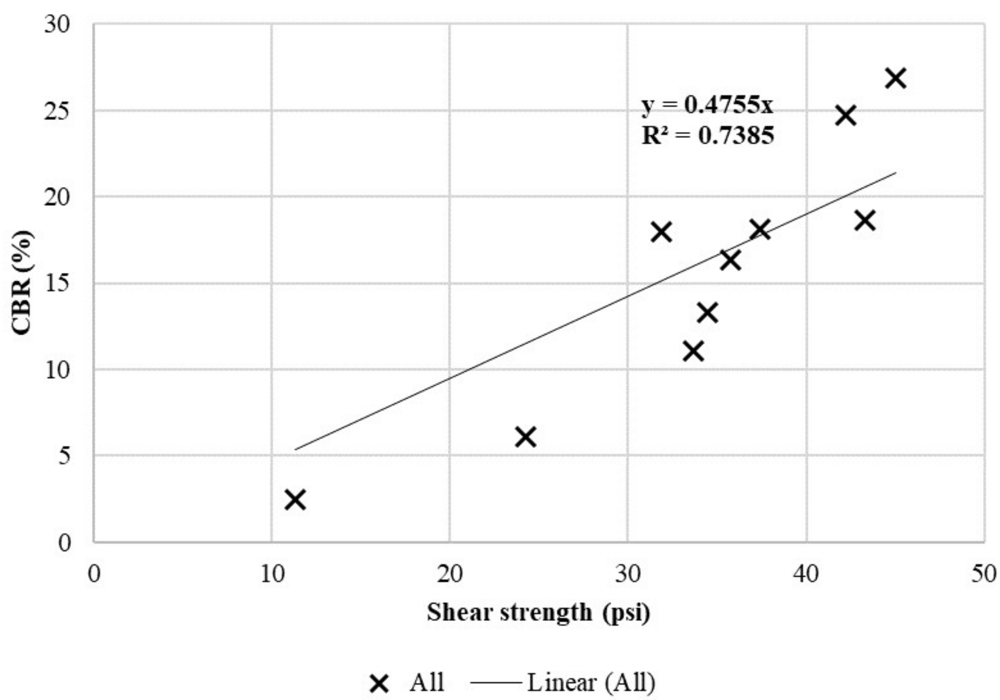


Figure 4. 4 CBR and shear strength (UCS) at wet of optimum conditions

The CBR and shear strength values obtained in this study are plotted with the existing correlation presented in Chapter 2 (See Figure 4. 5). The relationships proposed by Gregory and Cross (2007) and Giroud and Han (2004) are selected as these relationships gave upper and lower bound. As can be seen in Figure 4. 5, many data points appeared above the upper boundary line. This may be due to the existing relationships were developed based on the CBR measured at the maximum density of the soil sample. The selected shear strength and CBR values at MDD are shown in Figure 4. 6. The relationship between CBR and shear strength illustrated in Figure 4. 6 generally match that obtained in previous research work by Gregory and Cross (2007).

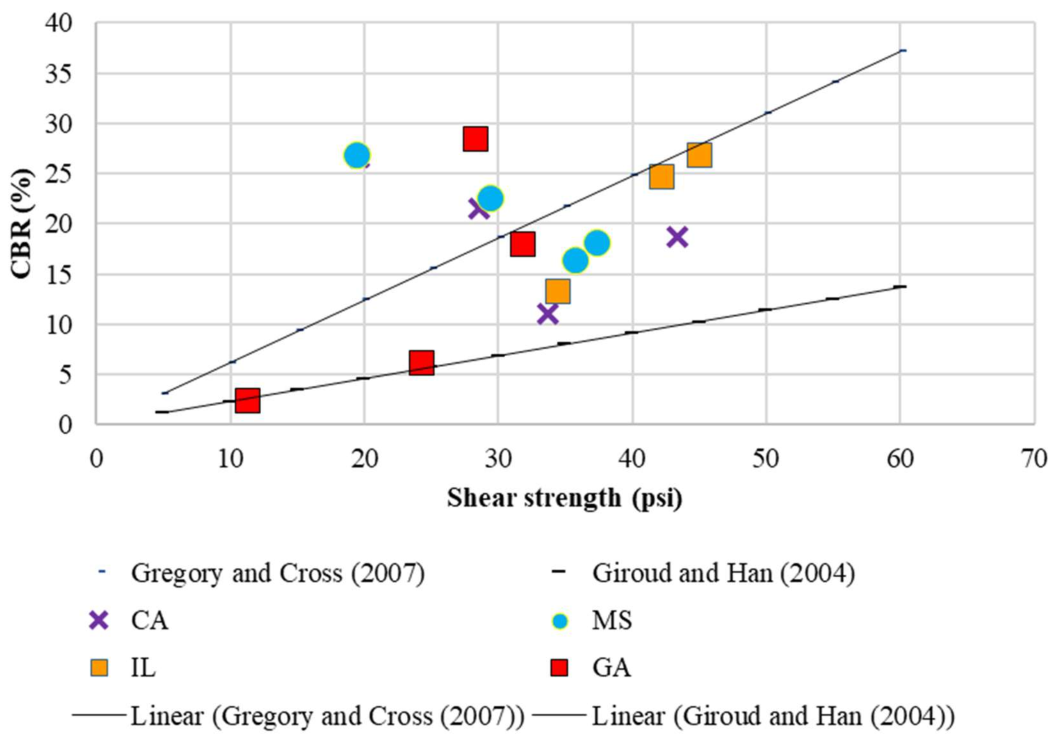


Figure 4. 5 Unsoaked CBR and shear strength vs. previous relationships

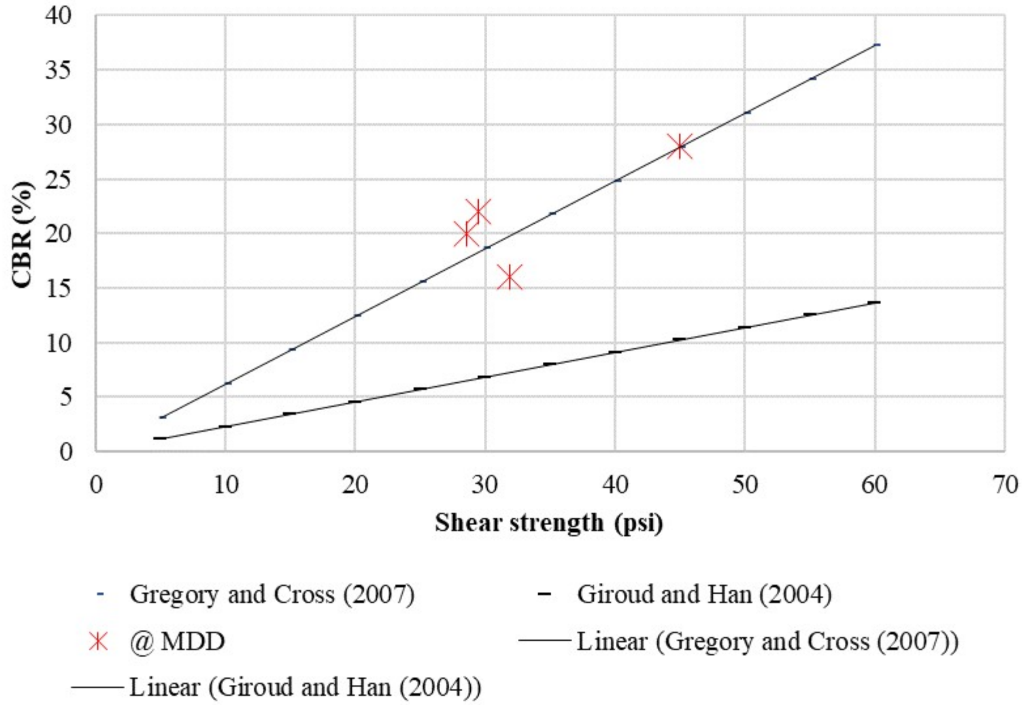


Figure 4. 6 Unsoaked CBR and shear strength at MDD vs. previous relationships

The relationships between shear strength and CBR presented in previous studies are based on soaked CBR. The unsoaked CBR values obtained in this study are converted to soaked CBR using the unsoaked vs. soaked CBR relationship shown in Figure 2. 4 (Arshad et al, 2018). And the trend is in good agreement with previous studies. (See Figure 4. 7). Figure 4. 6 is also updated with soaked CBR and the trend matches with previous research work by Giroud and Han (2004).

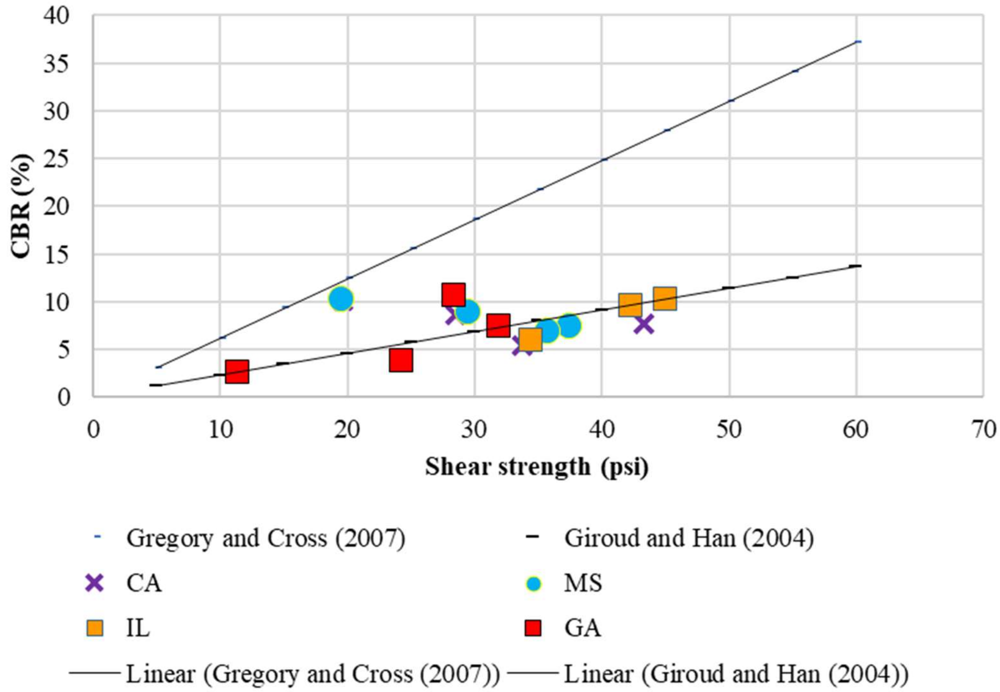


Figure 4. 7 Soaked CBR and shear strength vs. previous relationships

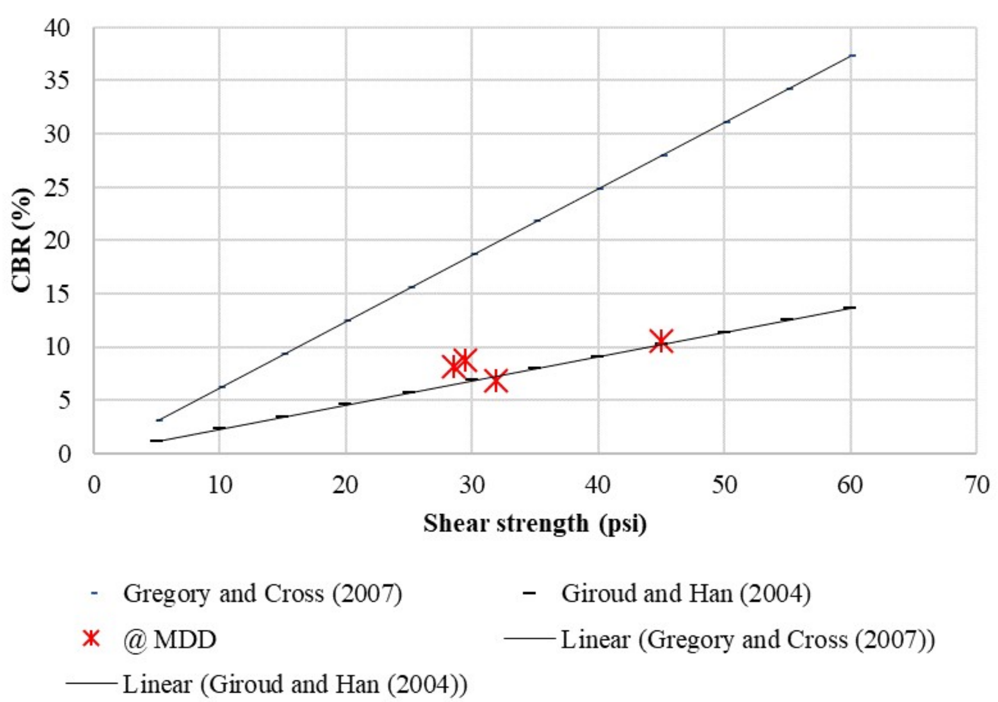


Figure 4. 8 Soaked CBR and shear strength at MDD vs. previous relationships

CHAPTER 5: CONCLUSIONS

The CBR is an important input property in the structural design of pavement. Due to the drawback of the CBR test, the design CBR values are often converted from other soil properties. Several research studies have been conducted to develop a relationship between the shear strength and the CBR values. A summary of the existing correlation formulas was produced and graphed together. A series of laboratory tests were performed with four different soil samples obtained from different parts of the U.S. Shear strength of the soil samples were determined with UCS test and various hand-held tools such as torvane, pocket penetrometer, and static cone.

The key findings are summarized below:

- Among all the shear strength tests, the UCS test provides most reliable shear strength value of the soil. The shear strength measured with handheld tool vary significantly or insensitive to the moisture content of soil.
- The relationship between CBR and shear strength developed based on the bearing capacity theory overpredicts the CBR value for the same shear strength.
- The CBR and shear strength of fine-grained soils show different trend with the change of the moisture content. CBR values decrease with an increase of moisture content while the dry density and shear strength increased with moisture content to a maximum value and decreases as moisture content increased more than the optimum.

Recommendations are provided below based on the findings of this study.

- UCS testing should be conducted to obtain the shear strength of soil.

- Further research will be needed to examine the effect of the compaction on CBR values. In this study, soil sample was compacted in three lifts with 25 blows from a 5.5-lb rammer.
- The relationship between unsoaked and soaked CBR should be evaluated by conducting more laboratory CBR tests.

References

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AASHTO T 208, “Standard Method of Test for Unconfined, Undrained Compressive Strength of Cohesive Soil.”

AASHTO T 216, “Standard Method of Test for One-Dimensional Consolidation Properties of Soils.”

AASHTO T 27, “Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregate.”

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AASHTO T 90, “Standard Method of Test for Determining the Plastic Limit and Plastic Index of Soils.”

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APPENDIX A: Data Tables

Table A- 1 Comparison of apparatus, sample, and procedure (AASHTO T99-180)

	T-99	T-180
DIAMETER	Method A,C : 4” Method B,D : 6”	Method A,C : 4” Method B,D : 6”
Mold height, in	4.584	4.584
Detachable collar height, in	2	2
Rammer diameter, in	2	2
Rammer mass, lb	5.5	10
Rammer drop, in	12	18
Blows per layer	Method A,C : 25 Method B,D : 56	Method A,C : 25 Method B,D : 56
Test sample size, lb	A : 7, B: 16, C: 12, D: 25	A : 7, B: 16, C: 12, D: 25

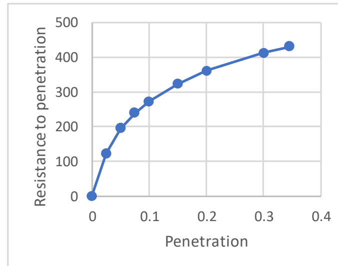
Table A- 2 CBR load output from loading device (IL)

Soil sample ID: IL

Piston Area 3.00 in^2

Moisture content: 13.23 %

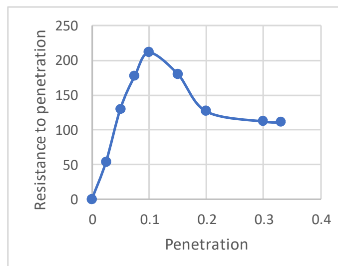
Load	Pressure	Displacement
lb	psi	in
0	0	0
371.20	123.79	0.03
587.66	195.97	0.05
717.14	239.15	0.08
818.30	272.88	0.10
968.56	322.99	0.15
1079.73	360.06	0.20
1234.63	411.72	0.30
1291.23	430.59	0.35



CBR 24.00%

Moisture content: 15.4 %

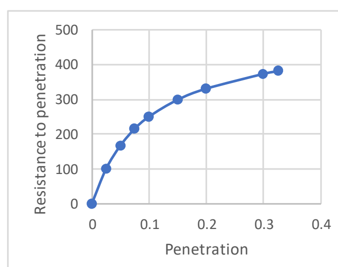
Load	Pressure	Displacement
lb	psi	in
0	0	0
162.89	54.32	0.03
391.21	130.46	0.05
533.47	177.90	0.08
633.39	211.22	0.10
541.32	180.52	0.15
380.28	126.81	0.20
337.17	112.44	0.30
332.71	110.95	0.33



CBR 21.12%

Moisture content: 16.13 %

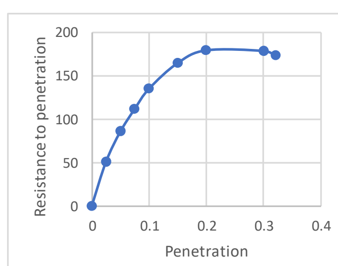
Load	Pressure	Displacement
lb	psi	in
0	0	0
302.07	100.73	0.03
503.76	167.99	0.05
647.56	215.94	0.08
752.25	250.85	0.10
898.36	299.58	0.15
992.12	330.85	0.20
1119.62	373.36	0.30
1143.42	381.30	0.33



CBR 22.06%

Moisture content: 18.75 %

Load	Pressure	Displacement
lb	psi	in
0	0	0
153.96	51.34	0.03
257.73	85.95	0.05
335.47	111.87	0.08
404.76	134.98	0.10
492.51	164.24	0.15
537.01	179.08	0.20
534.85	178.36	0.30
520.07	173.43	0.32



CBR 11.94%

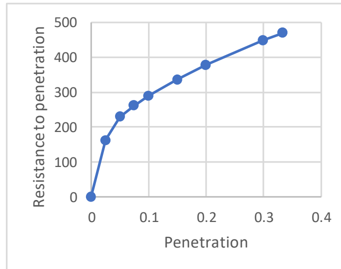
Table A- 3 CBR load output from loading device (GA)

Soil sample ID: GA

Piston Area 3.00 in^2

Moisture content: 14.1 %

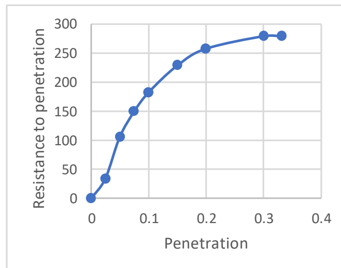
Load	Pressure	Displacement
lb	psi	in
0	0	0
488.37	162.86	0.03
690.67	230.32	0.05
783.97	261.43	0.08
867.11	289.16	0.10
1009.69	336.70	0.15
1133.79	378.09	0.20
1345.49	448.68	0.30
1406.09	468.89	0.33



CBR 25.21%

Moisture content: 17.53 %

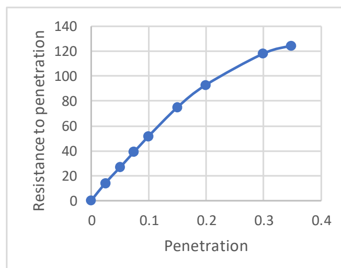
Load	Pressure	Displacement
lb	psi	in
0	0	0
102.85	34.30	0.03
317.46	105.86	0.05
448.18	149.46	0.08
547.63	182.62	0.10
686.20	228.83	0.15
772.72	257.68	0.20
836.93	279.09	0.30
836.62	278.99	0.33



CBR 17.18%

Moisture content: 20.27 %

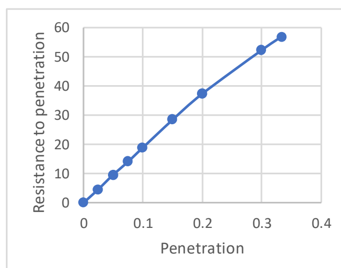
Load	Pressure	Displacement
lb	psi	in
0	0	0
42.49	14.17	0.03
79.90	26.65	0.05
117.62	39.22	0.08
155.03	51.70	0.10
224.47	74.86	0.15
278.36	92.83	0.20
353.80	117.98	0.30
372.58	124.25	0.35



CBR 6.19%

Moisture content: 22.62 %

Load	Pressure	Displacement
lb	psi	in
0	0	0
13.70	4.57	0.03
28.64	9.55	0.05
42.19	14.07	0.08
56.66	18.89	0.10
85.14	28.39	0.15
111.62	37.22	0.20
156.58	52.21	0.30
170.43	56.83	0.33



CBR 2.48%

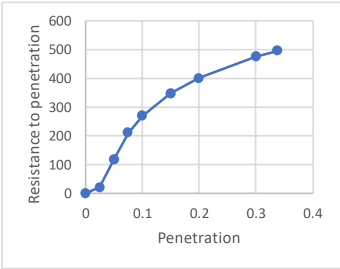
Table A- 4 CBR load output from loading device (CA)

Soil sample ID: CA

Piston Area 3.00 in^2

Moisture content: 7.91 %

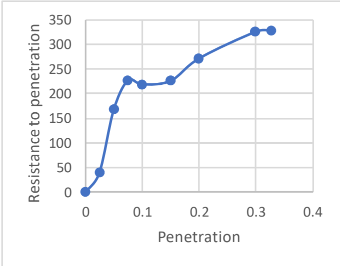
Load	Pressure	Displacement
lb	psi	in
0	0	0
66.36	22.13	0.03
358.11	119.42	0.05
632.78	211.01	0.08
808.44	269.59	0.10
1041.54	347.33	0.15
1201.34	400.61	0.20
1425.84	475.48	0.30
1488.34	496.32	0.34



CBR 26.71%

Moisture content: 11.22 %

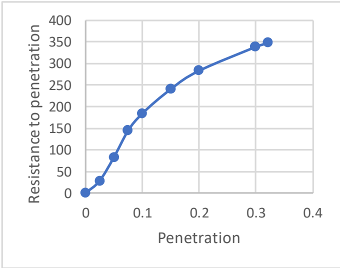
Load	Pressure	Displacement
lb	psi	in
0	0	0
119.02	39.69	0.03
502.84	167.68	0.05
678.97	226.42	0.08
655.26	218.51	0.10
676.35	225.54	0.15
813.07	271.14	0.20
975.34	325.25	0.30
980.58	327.00	0.33



CBR 18.08%

Moisture content: 13.66 %

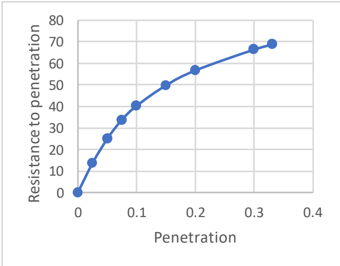
Load	Pressure	Displacement
lb	psi	in
0	0	0
85.14	28.39	0.03
248.33	82.81	0.05
433.70	144.63	0.08
553.79	184.68	0.10
723.45	241.25	0.15
851.09	283.82	0.20
1017.71	339.38	0.30
1045.41	348.62	0.32



CBR 18.92%

Moisture content: 21.41 %

Load	Pressure	Displacement
lb	psi	in
0	0	0
40.95	13.66	0.03
74.82	24.95	0.05
101.46	33.83	0.08
120.86	40.30	0.10
149.65	49.90	0.15
170.28	56.78	0.20
199.38	66.49	0.30
206.46	68.85	0.33

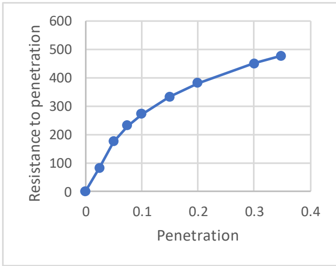


CBR 3.79%

Table A- 5 CBR load output from loading device (MS)

Soil sample ID: MS
Piston Area 3.00 in^2
Moisture content: 15.84 %

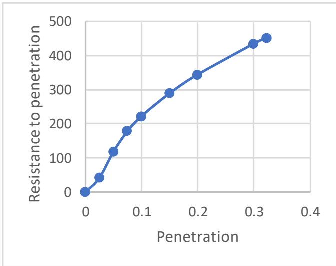
Load	Pressure	Displacement
lb	psi	in
0	0	0
248.34	82.81	0.03
527.93	176.05	0.05
695.29	231.86	0.08
817.68	272.67	0.10
1000.43	333.62	0.15
1143.78	381.42	0.20
1350.98	450.51	0.30
1428.18	476.26	0.35



CBR 25.43%

Moisture content: 17.18 %

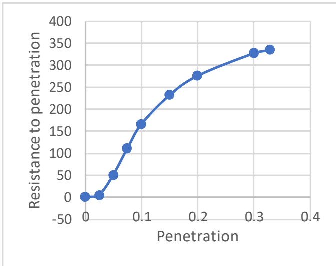
Load	Pressure	Displacement
lb	psi	in
0	0	0
124.40	41.48	0.03
351.80	117.31	0.05
534.55	178.26	0.08
664.65	221.64	0.10
865.41	288.59	0.15
1030.48	343.64	0.20
1300.68	433.74	0.30
1353.78	451.45	0.32



CBR 22.91%

Moisture content: 20.86 %

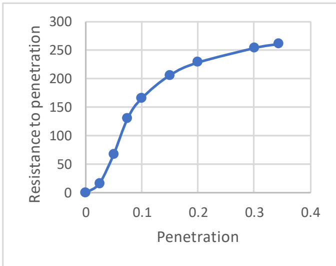
Load	Pressure	Displacement
lb	psi	in
0	0	0
14.93	4.98	0.03
148.88	49.65	0.05
329.17	109.77	0.08
496.68	165.63	0.10
693.75	231.35	0.15
827.23	275.86	0.20
981.81	327.41	0.30
1003.21	334.54	0.33



CBR 18.39%

Moisture content: 25.54 %

Load	Pressure	Displacement
lb	psi	in
0	0	0
50.65	16.89	0.03
201.38	67.15	0.05
391.37	130.51	0.08
497.14	165.78	0.10
618.92	206.39	0.15
685.89	228.72	0.20
761.64	253.99	0.30
783.51	261.28	0.34



CBR 15.25%